

Camera-based In-time Detection of Intruder Aircraft

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Abstract—This paper is the initiation of work dealing with intruder detectability and avoidability in aircraft sense and avoid. It considers dynamic capabilities of a specific own aircraft and real flight test results with two UAVs with homogeneous sky background conditions. From this data it tries to extrapolate detectability results to other intruders and camera systems and makes a basic estimation of avoidance capability.

Index Terms—Aircraft sense and avoid, camera, detection distance, decision time frame

I. INTRODUCTION

We are witnessing the rapid development of UAV technology nowadays. However, a significant barrier to the introduction of these devices to the airspace is the missing safety features, like robust autonomous navigation which assumes reliable midair collision avoidance among other important things. Robust midair collision avoidance assumes the detection of the intruder in non-cooperative situations, for what the most straightforward method is the application of an appropriate vision system for small or medium sized UAVs (call this as sense and avoid system). Visual detection of a remote intruder aircraft at the edge of the detection distance provides only angular value, but neither distance, nor intruder size and speed are detected. In this paper, we study how the intruder size, the intruder speed, the detection distance and the optical parameters of the vision system interrelates, and how the time frame for decision at the detection boundary depends on the optics and the camera resolution. Our goal is to explore the detection ranges and time frames for different intruder types considering a given own aircraft and multiple camera systems. The possibility to avoid the threat by the own aircraft is also examined. It is hard to find an exhaustive reference about this topic in the literature while these calculations are

very important before applying any vision-based sense and avoid system. In [1] an exhaustive research is done considering aircraft visibility by human observers. [2] and [3] deal with camera image-based observation of aircraft considering different camera setups but referencing only one specific intruder type. So there is lack of an exhaustive research with several intruder aircraft types. The paper is organized in the following way. In Section II, the difficulty to detect an aircraft by a vision system is discussed, in Section III the characterization of intruder aircraft from sense and avoid point of view is discussed while Section IV introduces the main results about detectability and avoidability of intruders. Finally, Section V concludes the paper.

II. ELECTRO-OPTICAL SYSTEM

The critical question of an electro-optical system application in sense and avoid (S&A) is the detectability of intruders. Figs. 1 and 2 show the minimal pixel resolution on the focal plane, what the system should reach. As it is shown in Fig. 1, a solid round shaped object above 6 pixel diameter is detectable against non-structured (clear sky or middle of a non-structured cloud, non-structured fields or forests large distance from the intruder aircraft) background. However, in case of a fixed wing aircraft (Fig. 2), in a worst-case scenario, the wingspan should reach 30 pixels for stable detection. As the aircraft is against structured background (edge of a cloud, structured cloud, structured ground), even above 50 pixels wingspan image can be required and the detection is still difficult in many situations.

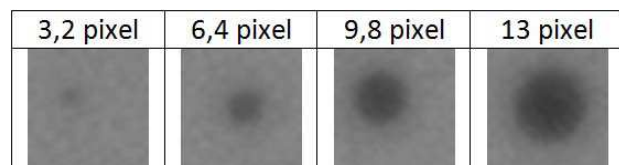


Fig. 1. Round shaped test objects with different diameters.

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For different performance and detection distances, here we show four camera - lens configurations for intruder detection (Table I). The first three of them are global shutter cameras, while the last one is a rolling shutter camera. In our application, where the local aircraft-like patterns of the large image is searched, the rolling shutter camera can be used as well as the global shutter cameras. The detection distance and the time frame figures depend on the camera parameters, intruder aircraft size and speed. These are calculated in Section IV.

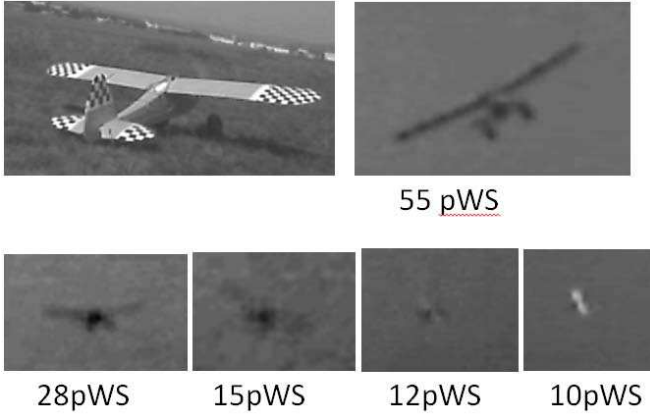


Fig. 2. 1.4 m wingspan aircraft on the ground and in air from different distances. Pixel sizes shows the wingspan of the silhouette.

TABLE I
CAMERA DATA

Type	Basler dcA	Basler acA	Basler acA	Basler acA
	1280	1440	2040	2500
Pixel count [Mp]	1.2	1.6	3	5
Camera resolution	1280 × 960	1440 × 1080	2048 × 1536	2592 × 1944
Pixel pitch [μm]	3.75	3.45	3.45	2.2
Focal length [mm]	3.74	4.2	6	4
Focal length f [px]	997.3	1217.4	1739.1	1818.2
View angle [$^\circ$]	65.4	61.2	61	71
MIN size S [px]	8	9	9	14

TABLE II
LITERATURE CAMERA DATA

Reference	[2]	[3]
Camera resolution	2048 × 2048	1440 × 1080
Focal length [px]	8987.5	1530
View angle [$^\circ$]	13	50.4

III. INTRUDER AIRCRAFT CHARACTERIZATION

The possible types of intruder aircraft to be detected by the onboard S&A system can be explored based-on the airspace categories where the UAV is intended to be used. The possible airspace categories can be selected based on [4] which makes an important effort to set S&A system effectiveness standards considering different class of UAVs and airspaces. The targeted airspaces by small UAVs can be Class D/E and G which does

not require on-board transponder or ATC link. Considering the possible threats, in Class D/E airspaces the intruder aircraft can range from micro UAVs through general aviation (GA) aircraft until large airliners / transporters on their approach to airports. So, these types should be characterized. [4] characterizes aircraft based-on their weight and speed, however from a vision sensor point of view it is better to use size and speed.

Intruder aircraft can be characterized by wingspan (b), fuselage length (L), height (H) and cruise speed. Such characteristics were collected from [5] ranging from CAP-10 to Airbus A380 and AN-225 including also helicopters.

Considering intruder detectability its average horizontal size $R = \frac{(b+L)}{2}$ will be the dominant dimension. From this size the average detection distance can (and will be in Section IV) be estimated if the camera parameters are known. From the point of view of the avoidance maneuver it is important to know also the cruise speed of the intruder to have an estimate of the time frame available to make the decision and complete the avoidance maneuver.

Based-on data from [5] a nomogram was built including possible intruder aircraft characteristic horizontal sizes and minimum, mean and maximum cruise velocities. It is shown in Fig. 3. The red stars denote the real aircraft data obtained from [5] lower and upper bounds were characterized by set of curves. For sizes below 7-8m our experiences with UAVs were used to characterize lower and upper cruise speed bounds.

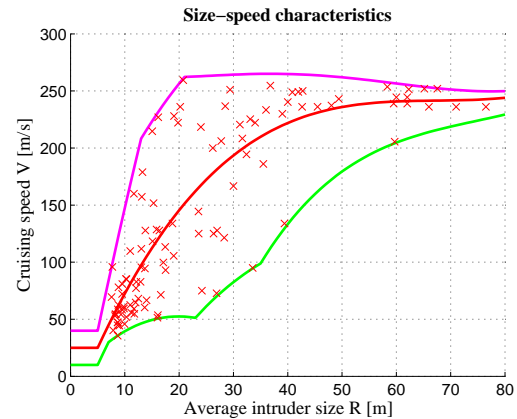


Fig. 3. Possible intruder aircraft sizes and related cruise speeds

IV. DETECTABILITY AND AVOIDABILITY RESULTS

Regarding detectability this study only considers camera resolution and a minimum area on the image sensor to be occupied by the object to continuously track it by the system. Neither homogeneity of the background nor contrast parameters are considered. Based on camera parameters a maximum distance can be calculated for any object size from which the object is detectable and also trackable.

However, considering avoidability which means the capability of our system to avoid the intruder in time, this depends on the detection distance, the relative velocity between the two aircraft and the dynamical capabilities of our own aircraft. We did several in-flight S&A tests between two UAVs (see videos on our Youtube / AeroGNC channel and [6]) from which the

dynamic capabilities of our own Sindy (see Fig. 4) aircraft can be estimated. We executed avoidance as a maximum bank turn into the opposite direction for a given time and then a slow turn back to the original trajectory. Not surprisingly start of avoidance does not mean a sudden change in the distance between the two aircraft as bank angle control and bank to turn rate dynamics both have a transient. Fig. 5 and Table III well show the gradual increase of absolute cross track distance relative to the own trajectory which characterizes the increase of distance also between the two aircraft. The red circles in the figure are the 'time stamps' related to the Times in the table. The thick continuous line is the average curve of all left and right turn curves which values are shown in the Table together with the time stamps. The Table shows that side distance starts to highly increase only after 2 seconds, below this time the avoidance will not be effective. Considering also the at least 2-3 seconds required time between first detection and decision about avoidance at least 5-6 seconds are required between detection and collision (or near collision) to safely avoid a small aircraft.



Fig. 4. Sindy 3.5m wingspan, 12kg own aircraft

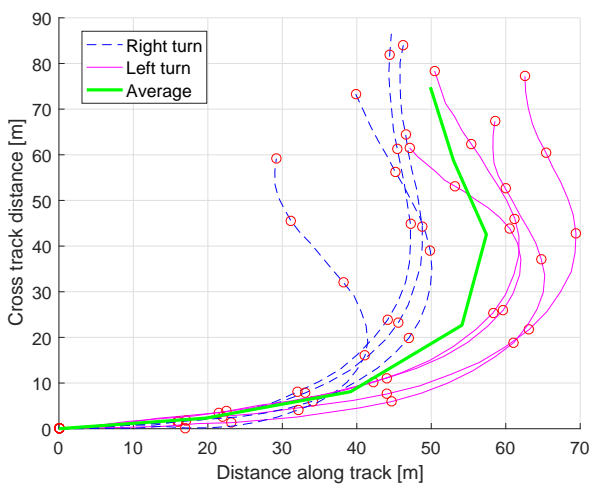


Fig. 5. Left / right avoidance maneuver trajectories

Going back to detectability our Basler dcA 1280 camera system was able to detect and track a 1.27m small intruder aircraft from 160-170m in the real flight tests with homogeneous background. Considering the $f = 997.3px$ focal length, the

TABLE III
GAINED AVERAGE DISTANCES

Time [s]	0	1	2	3	4	5	6
Distance [m]	0	2.3	8.1	22.7	42.54	58.7	74.8

$R = 1.27m$ intruder size and the $Z = 165m$ average detection distance the average pixel size from which the intruder was trackable results as: $S = \frac{f \cdot R}{Z} = 7.68px \approx 8px$. This is a much lower value than the values referenced in Section II for complicated backgrounds. This means a $8 \cdot 3.75 \cdot 10^{-6} = 30\mu m$ image size on the sensor. From this occupied size the minimum trackable pixel numbers (MIn size S) can be calculated for the other cameras in table I considering their pixel pitches and assuming that trackability depends on the occupied physical sensor size.

From this point the maximum detection distance of different size intruders from Fig. 3 can be calculated as $Z_D = f \frac{R}{S}$ for the range $R = 7 \dots 80m$ for which we have real aircraft data from [5]. These calculations were done for all four cameras from Table I. The results are shown in Fig. 6. The vertical lines are the sizes of the aircraft from the human visibility study summarized in Table IV. There, the worst range is for the worst contrast and the best is for the best in a computer simulation where human participants had to detect the aircraft in artificial images. Our detectability results for the same sizes are summarized in Table V. We do not have an exact value of the contrast of our reference measurements based-on which the minimum $8px$ detectable size was determined. The worst values of our detectability results are about two times higher than the worst human values while our best ones are about one third of the best human ones. More precise comparison would need precise contrast information of our collected images.

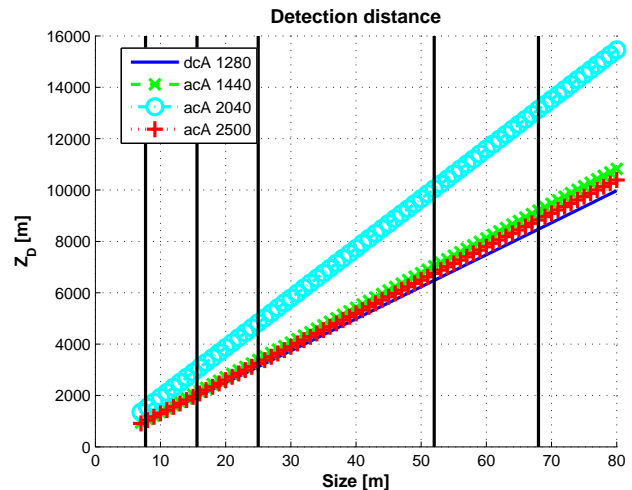


Fig. 6. Detection distances for different intruder sizes with different cameras

In [3] a Cessna aircraft with $R = 9.5m$ average size was detected from about 3700m with the camera referenced in Table II. Our results for this size are 1184m to 1835m however, in [3] the aircraft was considered as detected with as small as $3.5px$ image size. With such a small size there

is the possibility to have uncertain tracking of the object, so our results consider more stable tracking situations (first observation and continuous tracking are not the same).

In [2] an $R = 9m$ average size aircraft was tracked from 4-6km with a high precision (and so narrow view) camera referenced in Table II. The usage of this kind of camera onboard a flying aircraft has the possibility to easily lose the intruder from camera FOV. In the referenced article ground measurements were done increasing the possible precision.

TABLE IV
HUMAN VISIBILITY RESULTS FROM [1]

AC type	Size [m]	Worst range [m]	Best range [m]
Boeing 747	68	3950	39900
Boeing C-17	52	2580	29000
Embraer ERJ-145	25	1225	11120
MQ-9 Reaper	15.6	873	8900
MQ-8 Firescout	7.7	444	5030

TABLE V
CAMERA SYSTEM DETECTABILITY RESULTS

AC type	Size [m]	Worst range [m]	Best range [m]
Boeing 747	68	8477	13140
Boeing C-17	52	6482	10048
Embraer ERJ-145	25	3117	4830
MQ-9 Reaper	15.6	1945	3014
MQ-8 Firescout	7.7	960	1488

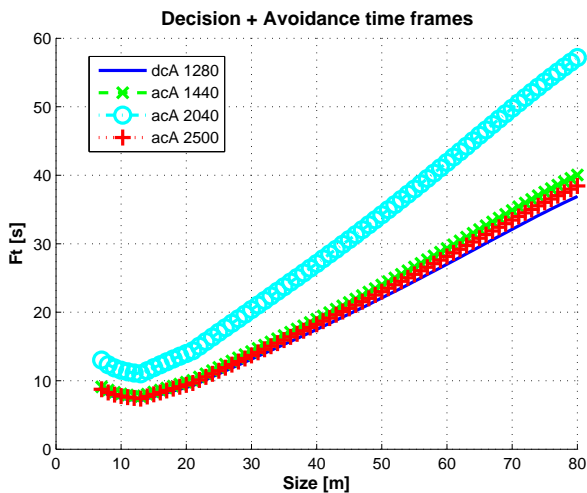


Fig. 7. Decision plus avoidance time frames for different intruder sizes with different cameras

Considering the $20m/s$ velocity of the Sindy own aircraft and the maximum cruise velocities of the considered intruders from Fig. 3 its easy to calculate the maximum relative velocities and from these and the detection distance the minimum time frames available to make the decision and execute avoidance (Ft). These results are shown in Fig. 7 for the different cameras. The figure shows that at least 7 seconds are available with any camera for any intruder size. This means

that if the decision about the possibility of collision requires 3 seconds than Sindy has at least 4 seconds for the avoidance and so can gain at least about 40m distance from the intruder. This can be sufficient to avoid collision.

V. CONCLUSION

The main topic of this paper is to estimate the possible maximum detection distances of different aerial vehicle intruders in aircraft sense and avoid. The calculations are based-on real flight results of a UAV pair one equipped with the camera system (own aircraft) and one intruder with homogeneous background conditions. These results are 'extrapolated' to different intruder and camera types. Another important factor in vision-based sense and avoid is the time frame to make the decision and execute avoidance if required. Knowing the cruise speed of the own aircraft and the intruders this time frame is easily estimated from the detection distance. Before the application of the sense and avoid system on the own aircraft its maneuvering capabilities should be compared with the available time frame to estimate the possibility of successful avoidance. This is also done in the article.

Future research can include consideration of different backgrounds and lighting conditions and the more precise characterization of decision time to get more realistic estimates about the possibility of avoidance.

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