Applicability of Different Mono Camera-based Aircraft Sense and Avoid Methods for Steady and Linear Path Intruders

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***Abstract*— This paper presents different mono camera-based aircraft sense and avoid methods considering linear and nonlinear own flight trajectories and steady and linear trajectory intruders. It introduces a method which in certain circumstances is capable to estimate intruder absolute position and velocity. Its relation to a previously published method is formulated and its reduced version considering steady intruders is also shown. The limitations and advantages of all methods are evaluated mathematically and in Matlab tests and finally a list of their capabilities and application guidelines are provided.**

I. INTRODUCTION

Sense and avoid (S&A) capability is a crucial ability for the future unmanned aerial vehicles (UAVs). It is vital to integrate civilian and governmental UAVs into the common airspace according to [1] for example. Besides aerial vehicles the avoidance of ground obstacles - such as transmission towers, tower-cranes, smokestacks, buildings or even tall trees - is important in case of low level flight and becomes more important considering the targeted integration of UAVs into the urban areas. During landing or in case of emergency landing the presence of ground vehicles and buildings can also be dangerous and should lead to a go-around or landing place modification (see the EU-Japan H2020 research project [2], [3]). This means that a small UAV's S&A system should be prepared to detect and avoid both aerial and ground obstacles (from now on intruder and obstacle will be used interchangeably).

In case of small UAVs the size, weight and power consumption of the onboard S&A system should be minimal. Monocular vision-based solutions can be cost and weight effective therefore especially good for small UAVs in aerial or ground object S&A [4], [5], [6], [7], [8], [9], [10], [11]. These systems basically measure the position (bearing) and size of intruder aircraft (A/C) camera image without range and intruder size information. This leads to the question of bearing-only target motion analysis (see e. g. [12], [13] and [14]) and in certain circumstances to a scale ambiguity making intruder size and absolute position estimation impossible.

Previous works of the author of this article focused on the development of S&A system applying monocular camera with on-board image processing. Considering aerial intruders the movement of both A/C was restricted to constant velocity and linear trajectories in e. g. [15], [16] and [17]. The developed solution estimates the so-called closest point of approach (CPA) relative to the unknown intruder size and the time to reach it (t_{CPA}). The ground obstacle related works considered free own trajectories but steady obstacles [18], [19] and [20] finally providing a method to estimate the obstacle's absolute position (relative to the own position upon observation of the obstacle) and size.

The current work targets several topics to step towards a complex S&A system able to handle both steady and moving aerial and ground obstacles:

- Formulate the equations for intruders moving with constant velocity on a linear path and consider the steady obstacle case as a reduction.
- Find the relation between the formulae for absolute coordinates and the method giving size relative CPA and t_{CPA}
- Explore the limitations of the different methods and give application guidelines.

The structure of the paper is as follows. Section II introduces the basic camera measurement equations, the derived different formulae to estimate obstacle parameters and their limitations. Section III introduces the different required application conditions and explores the possible decisions between the different methods. Section IV introduces the ideal evaluation environment and the test results with the different methods. Finally, Section V concludes the paper.

II. SENSE AND AVOID FORMULAE

In this work only the horizontal collision situation is considered as if this is solved than extension to the vertical dimension is straightforward (see [17] and [20]). Fig. 1 shows this situation between two aircraft flying on linear trajectories. X_a is the minimum absolute distance between them. Considering the unknown characteristic intruder size

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R the relative CPA can be defined as $CPA = X_a/R$ and its angle relative to the own aircraft trajectory is β_{CPA}. TTCPA denotes the Time to closest point of approach t_{CPA} required to reach CPA from the current position. In case of steady intruder $\beta_{CPA} = \pm 90°$ as the smallest distance from own trajectory is the perpendicular one (see [18]).

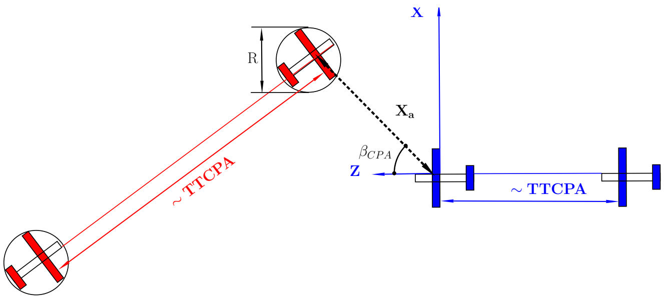

Fig. 1. Define TTCPA and CPA (intruder red from left, own aircraft blue from right)

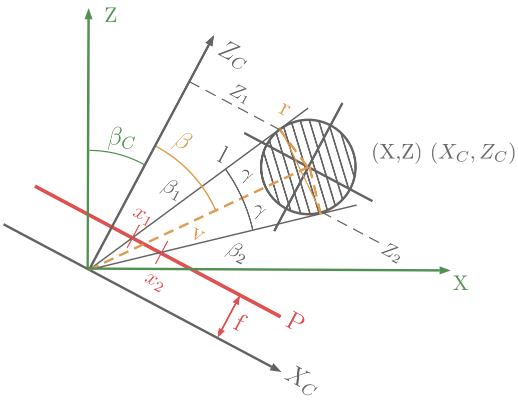

Fig. 2. Oblique camera disc projection model

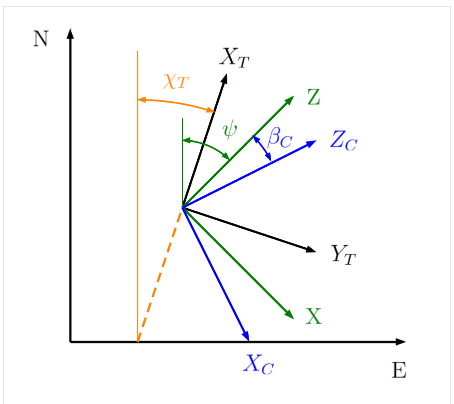

Fig. 3. The applied coordinate systems

Though rectangular shape models were explored for steady obstacles in [19] and [20] here only the disc projection model in Fig. 2 will be considered for simplicity with (X, Z) body and X_C, Z_C camera coordinate systems (β_C camera angle). All of the applied coordinate systems are shown in Fig. 3 including the N, E North-East (NE) and the X_T, Y_T trajectory systems. The latter is aligned with the average linear direction of the own flight in case of nonlinear flight trajectory. Transformation angles between the systems (χ_T, ψ, β_C) are also shown.

Regarding the intruder in this work steady or linear, constant velocity trajectories are considered in the NE system with Xi_0, Yi_0 starting position and Vi_x, Vi_y velocity components. The own aircraft can fly straight with constant velocity (linear trajectory) or non-straight (nonlinear trajectory) with any velocity having initial position Xo_0, Yo_0 and $Vo_x(t), Vo_y(t)$ velocity components in the NE system (here t shows the possible time dependence). For illustration see Fig.s 4 and 5.

To formulate the disc projection model in the camera system the relative distance between own and intruder should be calculated in NE and transformed into the camera frame. The transformation angle is $\beta_\psi = \psi + \beta_C$ according to Fig. 3. The relative distance in NE frame can be calculated as:

$$\begin{aligned} N &= Xi_0 + Vi_x t - Xo_0 - Vo_x t \\ E &= Yi_0 + Vi_y t - Yo_0 - Vo_y t \end{aligned} \tag{1}$$

Note that in case of time-varying $Vo_x(t), Vo_y(t)$ $Vo_x t$ and $Vo_y t$ should be substituted with $\int_{\tau=0}^{t} Vo_x(\tau) d\tau$ and $\int_{\tau=0}^{t} Vo_y(\tau) d\tau$. In camera frame the coordinates are (s and c are shorthand for sin and cos in the sequel):

$$\begin{aligned} X_C =& -s\beta_\psi(Xi_0 + Vi_x t - Xo_0 - Vo_x t) + \\ & c\beta_\psi(Yi_0 + Vi_y t - Yo_0 - Vo_y t) \\ Z_C =& c\beta_\psi(Xi_0 + Vi_x t - Xo_0 - Vo_x t) + \\ & s\beta_\psi(Yi_0 + Vi_y t - Yo_0 - Vo_y t) \end{aligned} \tag{2}$$

Considering the measurable image parameters in Fig. 2 S, β_1, β_2, x ($S = x_2 - x_1$ intruder image size and $x = (x_2 + x_1)/2$ intruder image centroid position) one can derive the approximate disc projection formulae (error analysis is presented in [16]) which relate X_C, Z_C to the measured parameters (here f is camera focal length):

$$\begin{aligned} \bar{S} &= S(\cos\beta_1 + \cos\beta_2) = \frac{2fR}{Z_C} \\ \bar{x} &= x\left(1 - \frac{\bar{S}^2}{16f^2}\right) = f\frac{X_C}{Z_C} \end{aligned} \tag{3}$$

Some reformulation gives favorable forms:

$$\frac{2f}{\bar{S}} = \frac{Z_C}{R} \qquad \frac{2\bar{x}}{\bar{S}} = \frac{X_C}{R} \tag{4}$$

Considering the current position of the own aircraft ($Xo(t) = Xo_0 + Vo_x t, Yo(t) = Yo_0 + Vo_y t$ or with the integrals) known and grouping the unknown variables gives a system of equations (SYS):

$$\begin{bmatrix} c\beta_\psi & s\beta_\psi & c\beta_\psi t & s\beta_\psi t & -(c\beta_\psi Xo(t)+s\beta_\psi Y_o(t)) \\ -s\beta_\psi & c\beta_\psi & -s\beta_\psi t & c\beta_\psi t & -(-s\beta_\psi Xo(t)+c\beta_\psi Y_o(t)) \end{bmatrix}$$
$$\begin{bmatrix} \frac{Xi_0}{R} & \frac{Yi_0}{R} & \frac{Vi_x}{R} & \frac{Vi_y}{R} & \frac{1}{R} \end{bmatrix}^T = \begin{bmatrix} \frac{2f}{S} \\ \frac{2x}{S} \end{bmatrix} \tag{5}$$

This system is very similar to the one applied in [20] for steady obstacles but this gives the absolute intruder initial position and also the velocity of non-steady intruders. It includes five unknowns and two equations so at least three image frames are required to have a solvable system. In practical applications its worth to consider 8-10 images with a moving window technique to better smooth out measurement noise.

In case of steady obstacles the Vi_x, Vi_y terms can be removed reducing the system to three unknowns (RSYS) though theoretically the full system should also give a valid solution with zero velocity estimates. Comparison of the precision of the full / reduced systems will be done later.

In case of linear own and intruder trajectories ($Xo(t) = Xo_0 + Vo_x t, Yo(t) = Yo_0 + Vo_y t$) the coefficient matrix of SYS will be rank deficient (the fifth column is a linear combination of the others) so the system is unsolvable (unobservable from the bearing as pointed out e. g. in [14]). In this case only a relative solution including CPA and t_{CPA} (referenced as TTCPA solution) can be obtained as published in [15], [17]. Now the goal is to establish a connection between the SYS and TTCPA solutions (published independently until now).

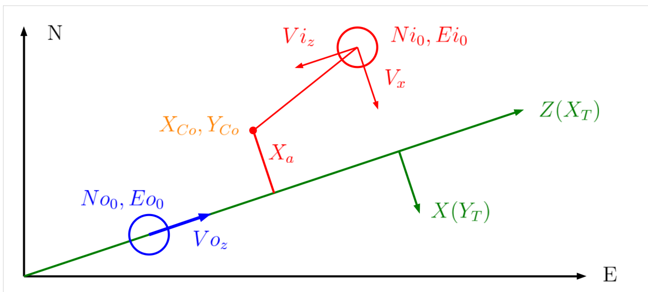

Fig. 4. Parameters in trajectory system

Fig. 4 shows the concept of the TTCPA solution considering the (linear) own trajectory relative parameters and assuming the body system (X,Z) aligned with the trajectory (X_T, Y_T). This can be achieved with ego motion transformation see e. g. [18]. As SYS considers the parameters in the NE system a relation should be established with the trajectory relative ones. Assuming a CPA at X_a distance from the trajectory (X_{Co}, Y_{Co}) the own and intruder NE initial positions can be formulated considering the trajectory relative velocity components and the fact that the aircraft reach X_{Co}, Y_{Co} at t_C absolute time:

$$\begin{aligned} \begin{bmatrix} Xo_0 \\ Yo_0 \end{bmatrix} &= \begin{bmatrix} X_{Co} + X_a s\chi_T - Vo_z t_C c\chi_T \\ Y_{Co} - X_a c\chi_T - Vo_z t_C s\chi_T \end{bmatrix} \\ \begin{bmatrix} Xi_0 \\ Yi_0 \end{bmatrix} &= \begin{bmatrix} X_{Co} - Vi_z t_C c\chi_T + V_x t_C s\chi_T \\ Y_{Co} - Vi_z t_C s\chi_T - V_x t_C c\chi_T \end{bmatrix} \end{aligned} \tag{6}$$

Reformulating (2) with $\beta_\psi = \chi_T$ in the trajectory aligned body system gives:

$$\begin{aligned} X = &- s\chi_T(Xi_0 - Xo_0 + (Vi_x - Vo_x)t) + \\ & c\chi_T(Yi_0 - Yo_0 + (Vi_y - Vo_y)t) \\ Z = & c\chi_T(Xi_0 - Xo_0 + (Vi_x - Vo_x)t) + \\ & s\chi_T(Yi_0 - Yo_0 + (Vi_y - Vo_y)t) \end{aligned} \tag{7}$$

Substituting the positions from (6), considering the construction of Vo_z, Vi_z, V_x from Vo_x, Vo_y, Vi_x, Vi_y and $t_{CPA} = t_C - t$ and making all the simplifications gives:

$$\begin{aligned} X &= X_a - V_x t_C + V_x t = X_a - V_x t_{CPA} \\ Z &= (Vo_z - Vi_z)t_C - (Vo_z - Vi_z)t = -V_z t_{CPA} \end{aligned} \tag{8}$$

From this point [15] gives the details to determine CPA and t_{CPA} for linear trajectory intruders (having only relative distance estimate not the absolute) and [18] a method to determine the size and absolute position of a steady obstacle.

III. DECISION SET

After defining (referencing) the possible formulae and listing their limitations the sense and avoid scenario and calculation possibilities can be summarized in Table I.

TABLE I
S&A SCENARIOS AND CALCULATION POSSIBILITIES

Own trajectory	linear		nonlinear	
Intruder trajectory	steady	linear	steady	linear
TTCPA calculation	valid	valid	invalid	invalid
Reduced SYS	valid	invalid	valid	invalid
Full SYS	invalid	invalid	≈ valid	valid

Here Reduced SYS (RSYS) means (5) without $Vi_x/R, Vi_y/R$ (only position and size are unknown). ≈ means approximate validity (system solvable but may be inaccurate). The table shows that to select the proper method one has to decide about the own trajectory (linear or nonlinear) and the state of the intruder (steady or moving on linear path).

A. Trajectory measure (TM)

To decide about the linearity of the own trajectory a measure is introduced. It is calculated from the moving window (N frames) own velocity and position data. The average flight direction can be calculated from the mean velocity components as

$$\chi_{AV} = \arctan\left(\frac{\sum_{i=1}^{N} Vo_y(i)}{\sum_{i=1}^{N} Vo_x(i)}\right)$$

Calculating also the average position a line can be defined through it pointing in the average direction. Summing up the absolute perpendicular distances of every position from this line gives a measure for the nonlinearity of the trajectory (having zero value if the trajectory is a line). Above a given threshold the own trajectory can be considered nonlinear.

B. Steady or linear intruder

Considering Table I in case of linear own trajectory both TTCPA [18] and RSYS (both giving absolute size and distance) can be applied for steady but only TTCPA [15] (giving only relative distance) is valid for moving intruders. A possible strategy can be to use RSYS if the intruder is steady and switch to TTCPA if its moving. In case of nonlinear own trajectory RSYS is preferred for steady obstacles (see test results later). However, both strategies need a confident decision about steady or linear trajectory intruder. This is examined in the next subsubsections.

1) Moving intruder detection with linear own trajectory: In case of steady intruder its estimated global position should be the same in every time step. So possibly from the change of the estimates the moving intruder can be detected. This requires to evaluate the behavior of RSYS in case of nonzero intruder velocity. Multiplying (5) by $\begin{bmatrix} c\beta_\psi & s\beta_\psi \\ -s\beta_\psi & c\beta_\psi \end{bmatrix}^{-1}$ from the left gives:

$$\frac{t}{R}\underbrace{\begin{bmatrix} Vi_x \\ Vi_y \end{bmatrix}}_{Vi}\Bigg| - \frac{t}{R}\underbrace{\begin{bmatrix} Vo_x \\ Vo_y \end{bmatrix}}_{Vo} + \frac{1}{R}\underbrace{\begin{bmatrix} Xi_0 \\ Yi_0 \end{bmatrix}}_{Pi_0} - \frac{1}{R}\underbrace{\begin{bmatrix} Xo_0 \\ Yo_0 \end{bmatrix}}_{Po_0} = RHS \tag{9}$$

In RSYS the leftmost term is not present in the equation. However, in case of moving intruder it is present in the system dynamics. Moving intruder is undetectable from the estimates if the effect of the leftmost term can be exactly covered by the estimated R, Xi_0, Yi_0. As the velocity terms depend on time the intruder velocity effect could possibly be covered by a false R estimate. Expressing intruder velocity vector with the scaled own and a remaining term: $Vi = \alpha Vo + Vo^{\perp}$ shows that the part parallel to the own velocity can be covered by a false R as $R' = \frac{R}{1+\alpha}$. The other $Vo^{\perp}$ can only be covered with false intruder position estimates as:

$$\begin{bmatrix} Xi'_0 \\ Yi'_0 \end{bmatrix} = \frac{1}{1+\alpha}\begin{bmatrix} Xi_0 \\ Yi_0 \end{bmatrix} + \frac{1}{1+\alpha} Vo^{\perp} t$$

This shows that if $Vo^{\perp} = 0$ (intruder linear trajectory parallel to own) then one gets a scaled but constant estimated intruder position so the moving intruder can not be detected. Unfortunately also the TTCPA method for steady intruder will estimate the same scaled parameters (this can be derived but omitted here) so there is no possibility to detect the moving intruder in every case. However, except for helicopters usually the steady obstacles are on the ground so their steady status can be detected from their background relative motion and then its possible to switch to RSYS, otherwise the TTCPA method for moving intruders should be applied as it gives correct relative results also for steady obstacles.

2) Moving intruder detection with nonlinear own trajectory: In case of nonlinear own trajectory (9) changes to:

$$\frac{t}{R}Vi\Bigg| - \frac{t}{R}\int_{\tau=0}^{t} Vo(\tau)d\tau + \frac{Pi_0}{R} - \frac{Po_0}{R} = RHS \tag{10}$$

Expressing

$$Vo(\tau) = \overline{V}o + \Delta Vo(\tau) = \alpha\overline{V}o + \overline{V}o^{\perp} + \Delta Vo(\tau)$$

shows that analogously to the previous subsubsection the moving intruder becomes undetectable if $\overline{V}o^{\perp} = 0$ and $\int_{\tau=0}^{t} \Delta Vo(\tau)d\tau = 0 \ \forall t$. The latter is only possible for linear own trajectory so if the own trajectory is nonlinear enough (proper threshold for TM) then the steady / moving intruder problem will always be decidable (see test results).

IV. TEST RESULTS

The decision possibilities and the precision of the methods are evaluated in Matlab in ideal conditions generating steady or linear moving intruder and linear or nonlinear own trajectories. The nonlinear own trajectory is constructed from a series of joined arcs with given fixed $L = 150m$ and different A amplitude parameters (see Fig. 5). The own velocity was constant 20m/s while the intruder was 15m/s. The orientation of the own aircraft follows the tangent of the arcs in every point. The intruder is modeled with a 10m diameter disc projected into the camera system with $f = 2000$ and an 80° field of view. Positions out of the field of view are declared undetected, no pixelization or other errors are applied. About 36s flight is simulated every time considering a realistic 10Hz image processing and 10 frames in the moving window (1s data in each step).

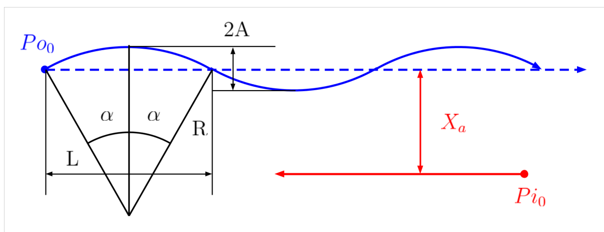

Fig. 5. Own and intruder test trajectories

The linear intruder trajectory (called linear intruder in the sequel) is parallel to the main line of the own trajectory in every test to have the most critical case from the observability point of view.

The first test examined the possibility to detect a linear intruder (instead of the steady) from the increased variance of estimated position (theoretically constant) applying the RSYS solution and considering different amplitude own trajectories. The considered trajectory amplitudes were $A =$

$[0 \quad 1 \quad 2 \quad 5 \quad 10]\, m$ (also for later cases). In Fig. 6 the variances of the position estimates are plotted from RSYS method considering steady and linear intruders against the average TM increasing with increased trajectory amplitude.

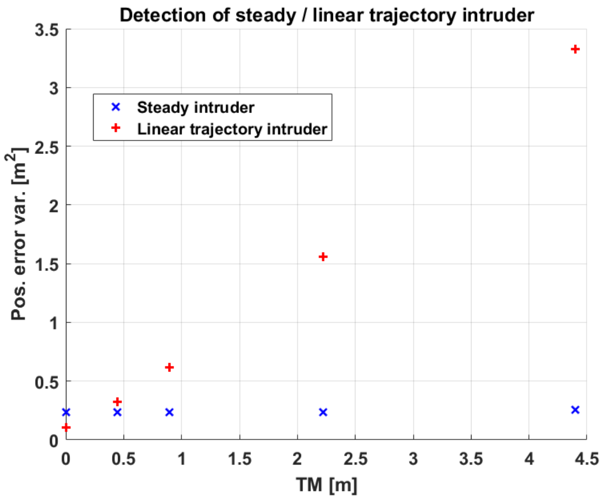

Fig. 6. Estimated position variances for steady / linear intruder

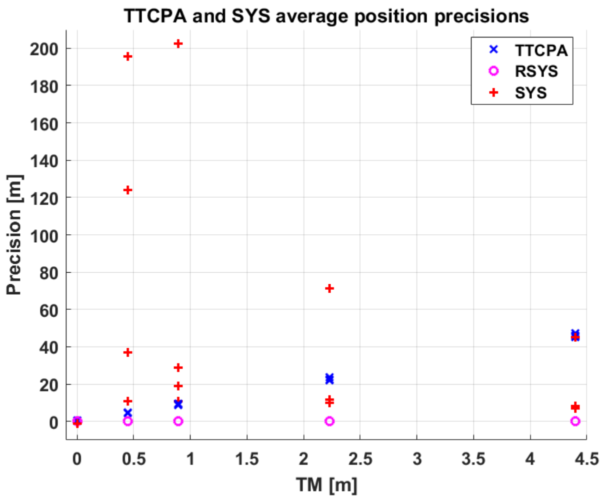

Fig. 7. Estimated position precision with the different methods for steady intruder

The figure shows that while the variances are about the same for the steady intruder irrespective of the own trajectory amplitude and TM in case of the linear intruder they increase with the increase in the amplitude and differ from the steady values. The figure verifies the unobservability of the linear intruder with parallel linear own trajectory as for the zero amplitude (zero TM) the variance of the position estimates is lower then for the steady intruder. For $A = 1m$ the linear intruder variance is larger so violation of the steady intruder assumption can possibly be detected also for this small amplitude. Of course with non-ideal noisy data possibly larger amplitudes are required to detect violation of the assumption (according to the figure the variance of the estimated position continuously increases with the amplitude of the trajectory).

The second test examined the performance of the different methods with the same own trajectories but with steady intruder considering different CPAs from the set $[0 \quad 2 \quad 5 \quad 10]$. The position estimation precision which is the average 2D distance of the estimated positions from the real one is determined and plotted for all cases in Fig. 7. The figure shows that as the TTCPA method is based-on a linear own trajectory assumption its performance degrades by increasing the amplitude of the nonlinear trajectory. The SYS method considering nonzero intruder velocity components can have enormously large errors in some cases but its precision increases as the amplitude increases. The RSYS method developed for this case gives almost the same errors for any parameter that is why SYS is only approximately valid (see Table I) and RSYS is preferred over and so the steady / linear position of the intruder should be decided.

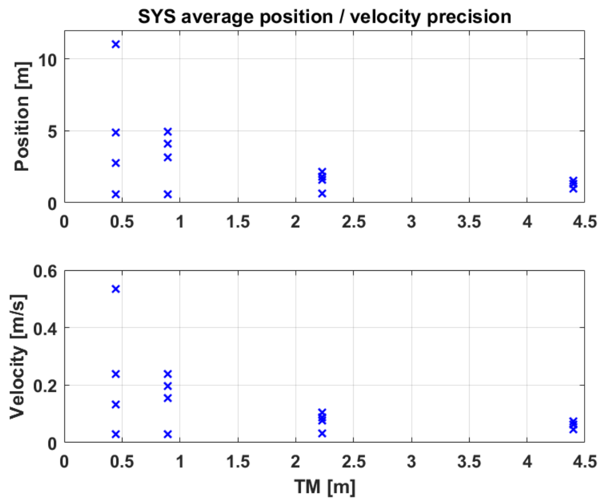

Fig. 8. Estimated position and velocity precision for linear intruder with SYS method

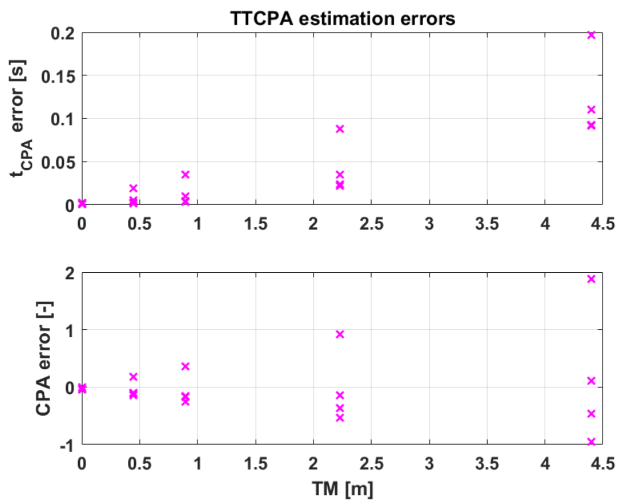

Fig. 9. Estimated TTCPA and CPA precision for linear intruder with TTCPA method

The third test examined the performance of the TTCPA and SYS methods considering linear intruder and the same amplitude and CPA data as above. In Fig. 8 the position and velocity estimation precision of the SYS method is plotted against TM showing unacceptable performance (in the position) for small amplitudes which improves into really good performance for 5m and 10m amplitudes. This verifies the system unobservability for linear or close to linear own trajectory. On the other hand the precision of the TTCPA method decreases both in t_{CPA} and CPA as the amplitude increases (see Fig. 9). The conclusion is that if the linear intruder movement is detected for linear or close to linear own trajectories the TTCPA while for nonlinear ones with persistent excitation the SYS method should be applied.

V. CONCLUSION

This paper proposes and evaluates three different monocular camera-based sense and avoid methods part of which was published in previous papers of the author. The first is SYS formulated here targeting to estimate the absolute position and velocity of the intruder moving on a straight trajectory. The second is a reduction of SYS (RSYS) without velocity estimation for steady intruders. The third is a time to closest point of approach (t_{CPA}) and CPA-based method (TTCPA) published before both for straight trajectory and steady intruders. A connection between the SYS and TTCPA methods is also formulated.

Applicability conditions were evaluated for linear and nonlinear own flight trajectories (with an introduced trajectory measure) and steady or linear trajectory intruders leading to the following conclusions and application rules. Limitations of the methods:

- SYS is unsolvable for linear own trajectories and inaccurate for steady intruder position.
- RSYS is solvable for any own trajectory, gives superior results for steady intruder but violation of the steady intruder assumption can not always be detected
- TTCPA is solvable only for linear own trajectories and both for steady and linear intruders. It basically gives distances relative to the intruder size and the time to be closest to the intruder. In case of steady intruder absolute coordinates and size can be determined from own velocity but RSYS method is valid for any own trajectory so it is better to be applied.

Application guidelines:

- In case of linear own trajectory apply the TTCPA method. If steady intruder is detected from e. g. image background relative motion switch to the RSYS method.
- In case of nonlinear own trajectory apply the RSYS method and run detection for linear intruder trajectory. If linear intruder trajectory is detected switch to the SYS method.

Future plans include evaluation of the above guidelines and methods in more realistic conditions considering pixelization, non-disc shape of the intruder and possible own position / velocity measurement errors. Another direction can be the consideration of non-straight intruder trajectories.

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