Obstacle Awareness and Collision Avoidance Radar Sensor System for Smart UAV

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Abstract

In this paper, the critical requirement for obstacle awareness and avoidance is assessed with the compliance of the equivalent level of safety regulation, and then the collision avoidance sensor system is presented with the key design parameters for the requirement of the smart unmanned aerial vehicle in low-altitude flight. Based on the assessment of various sensors, small-sized radar sensor is selected for the suitable candidate due to the real-time range and range-rate acquisition capability of the stationary and moving aircraft even under all-weather environments. Through the performance analysis for the system requirement, the conceptual design result of radar sensor model is proposed with the range detection probability and collision avoidance mode is established based on the time-to-collision, which is analyzed by collision scenario.

Introduction

Recently, Unmanned Aerial Vehicle(UAV) has been drawing a great attraction for the applications to both civil and military mission without risk in air safety for the pilot flying in low-altitude and/or in dangerous battlefield environment. Due to the inherent nature of the low flying vehicle, obstacle awareness is a fundamental requirement to avoid the collision against stationary and/or moving target obstacles along the flight path. Also it is noted that UAV should secure the equivalent level of safety comparable with manned aircraft in order to fly in civil and military airspace. Thus the collision avoidance system should be considered as a part of the navigation system in an unmanned vehicle. The obstacle awareness and collision avoidance is being acknowledged as the most important issues in the field of unmanned vehicle. An international standard regulation for the "sense-and-avoid" of UAV is being studied in Europe and USA, and the related technology has not been matured yet for the unmanned system application. Recent technology advances in obstacle detection using optical imaging sensor for aircraft[1] and laser radar for helicopter[2] have been addressed in the articles, but the radar sensor technology for obstacle awareness and collision avoidance is being under development[3] and has recently been demonstrated for the manned helicopter and unmanned vehicle[4]. The collision awareness and avoidance system is under feasibility study for the korea Smart UAV project, whose objective is to develop a smart UAV capable of high speed cruise and vertical take off/landing (VTOL) by integrating "smart" technologies over the years. In this paper, the characteristics of candidate sensor for collision avoidance are compared and the requirement for the radar sensor is assessed in terms of the system requirement and air safety regulation. Radar

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sensor based obstacle awareness and collision avoidance criteria. Finally, the millimeter radar detection performance and the collision avoidance mode are presented for the application to the unmanned vehicles in the typical flight environments.

Requirement Analysis of Collision Avoidance Sensor

The smart UAV program requires the collision avoidance capability to automatically sense and avoid the stationary obstacles and/or non-stationary moving objects along the flight path in the relatively low-altitude flying and rapid maneuvering environment. It is essential to consider that the applicable of providing the real-time position data measurement and accommodating the given payload avionics constraints such as weight, volume and power. Based on the system requirement, the key design parameters can be extended as follows.

System Requirement

Maximum speed of UAV is 500km/h without payload and 440km/h with payload. The surveillance mission payload is limited to less than 40kg and the separated collision avoidance payload is reserved for less than 25kg.

Sensor Requirement

The collision avoidance sensor selection should be considered in several important points of view : real-time measurement capability, operational environment, payload constraints and the air safety regulation. The most important requirement of the obstacle detection sensor for collision avoidance is the capabilities of real-time measurement of relative range, range-rate and bearing in azimuth and/or elevation. The operational environment of the vehicles is to be considered as the sensor selection criteria, which include the search and scan capability, vehicle maneuverability, endurance time in air and ECCM capability. The most critical constraints for small unmanned vehicles are the payload requirements. The payload weight requires less than 25kg and the volume limit requires 620mm(width)X420mm(height)X300mm(depth) for the space of the collision avoidance equipment in the vehicle. A low power and long life time reliability are to be requirement as well. Final consideration is to meet the air safety requirement flying in airspace as directed by FAA or international standard for "sense-and-avoid" requirement for UAV air safety, but at moment, as a upper bound of the regulation, the minimum requirement is to comply with the equivalent level of safety (ELOS) for "see-and-avoid" for manned aircraft pilot by the FAA regulation. Table 1 summarizes the key regulation for collision avoidance of the manned pilot

Collision Avoidance Mode

Three critical modes of operation are required to decide the status of the collision risk :

Table 1. "See-and-Avoid" ELOS

Performance Parameter	ELOS for See & Avoid
Missed Distance	500 feet
Field of Regard Azimuth / Elevation	Search Volume +/-60° , +/-10°
VFR Detection Range	1.84 miles
Time to Collision (11 sec avoidance maneuver)	21 sec (10 sec PRT) 23.5 sec (12.5 sec PRT) PRT : Pilot Reaction Time

search, awareness and avoidance modes. In a search mode, the system searches and monitors the obstacles within a certain scan volume along the flight path. Once the obstacles are detected from the sensor in a 23 sec of time-to-collision, the awareness mode is activated by tracking the position of the designated object. When time-to-collision is 11 sec, awareness mode is changed to the avoidance mode and the system initiates to maneuver and autonomously turn the vehicle in order to avoid the dangerous obstacles.

Considering these requirements, the non-cooperative methods using active radar sensor is being selected for the primary collision avoidance sensor. Especially, small-sized and light-weight millimeter wave radar sensor is being selected for the primary collision avoidance sensor. The cooperative method such as TCAS[5] and/or ADS-B could be considered to be an alternative option for back-up system.

Collision Avoidance Radar Sensor

OACAS Concept

The conceptual block diagram of the Obstacle Awareness and Collision Avoidance (OACAS) system is shown in Fig. 1[6].

The CAS system consists of radar sensor (CAR) and Obstacle Collision Avoidance System (OCAS) processor. Utilizing the radar sensor data of range, azimuth or elevation and velocity of the obstacles, the OCAS should decide the collision criteria and send the avoidance command to the DFCC(Digital Flight Control Computer) based on the time-to-collision criteria. Depending on the closing or opening speed of moving obstacles from the radar, the minimum required

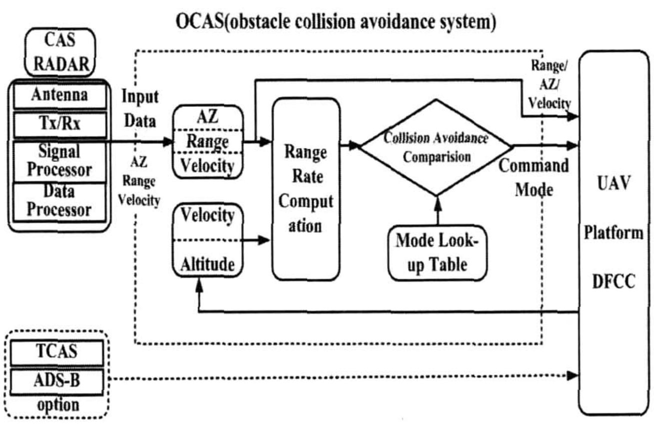

Fig. 1. Concept of OACAS

Table 2. Time-to-Collision Criteria

Velocity (km/h)	Time-to-Collision (sec)				
	5s	11s	17s	23s	25s
500	0.7km	1.5km	2.3km	3.2km	3.5km
600	0.8km	1.8km	2.8km	3.8km	4.2km
700	1.0km	2.1km	3.3km	4.5km	4.9km
800	1.1km	2.4km	3.8km	5.1km	5.6km
900	1.3km	2.8km	4.2km	5.8km	6.3km
1000	1.4km	3.0km	4.7km	6.4km	6.9km
Closing Speed		Avoidance Mode		Awareness Mode	

time-to-collision can be summarized in Table 2. In this case the UAV speed is assumed to be 440Km/h with payload.

CAS Radar Design Model

A CAS radar design model for collision avoidance is shown in Fig. 2.

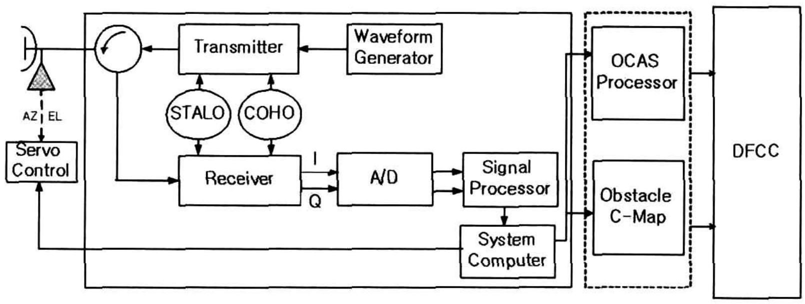

Fig. 2. Collision Avoidance Radar

The radar system model consists of antenna, transmitter, receiver, signal processor and system control computer. In addition the OCAS processor and the obstacle clutter map(C-map) may be included for the OACAS mission. The Typical radar design parameters are listed in Table 3[7].

Table 3. Typical Radar Sensor Model

Frequency	35 GHz
Detection Range	6.4 Km
PRF	5 KHz(LPRF) / 15 KHz(HPRF)
Range Resolution	5 m
Pulse Width	33 ns
Peak Power	3 Kw
Scan Coverage	180 deg(+90~-90)in Az 100 deg(+20~-80)in El
Scan Rate	150 deg/sec
Antenna Beamwidth	2.5 deg
Antenna Gain	38 dB
Receiver Noise Figure	3.5 dB
RCS	2~30 dBsm
Probability of False Alarm	10e-6
Probability of Detection	90% (SW model 2 & RCS 2 dB)

Radar Detection and Collision Avoidance Mode Performance

The collision avoidance problem using radar sensor may be separately considered in two cases. One is the awareness problem, which can be represented by the probability of detecting the obstacles which are statistically different RCS model in the unmanned vehicle environments. The other is the avoidance problem which can be represented by the performance of the collision avoidance mode based on the given radar range, range-rate and bearing information in the various flight scenarios.

Obstacle Detection Performance

Radar detection probability varies depending on SNR and/or false alarm rate. Also, SNR varies depending on RCS which may be fluctuated in amplitude(scintillation) and/or in phase (glint). For most cases, the glint can not be of major concern, but the cases where high precision and accuracy required, glint can be a detrimental. Scintillation can vary slowly or rapidly depending on the obstacle size, shape, dynamics and its relative motion with respect to radar. Due to the RCS changes as random process, the RCS scintillation model is used as a statistical model. The swering model is used for this simulation[8]. The typical obstacle RCS which is used for this simulation is listed in Table 4[9].

Table 4. Obstacle Model

Stationary Obstacle	Power Line	-20dBsm
	Building	15dBsm
	Wooden Hill	20dBsm
Moving Obstacle	Trainer	1.76dBsm
	Small Fighter	3.01dBsm
	Large Fighter	6.99dBsm

For given radar model parameter and the probability of false alarm, the SNR is compared with target RCS, and then the probability of detection is compared with range using SNR. Since the atmospheric attenuation is the main reason for decreasing SNR in millimeter wave bands, the attenuation according to range should be considered in radar equation. Clear air attenuation is adapted in this simulation. The probability of detection versus range according to Swerling model in dual mode PRF is shown in Fig. 3-9.

When it is the time-to-collision of 23sec for awareness mode in the closing speed of 1000km/h between UAV and moving obstacle, the distance between them becomes the minimum detection range of 6.4km for collision avoidance radar. In case of stationary obstacle, considering UAV maximum speed of 440km/h, the minimum detection range becomes 2.8km based on time-to-collision of 23sec. Fig. 3-7 shows the results of detection probability in low PRF mode, which are represented the probability of detection more than 90% at the minimum detection range except for power line in Swerling model v and small-sized aircraft in Swerling model i . In the high PRF mode, due to the number of integration pulses is increased in the constant dwell time, which also increases the SNR, power line and small-sized

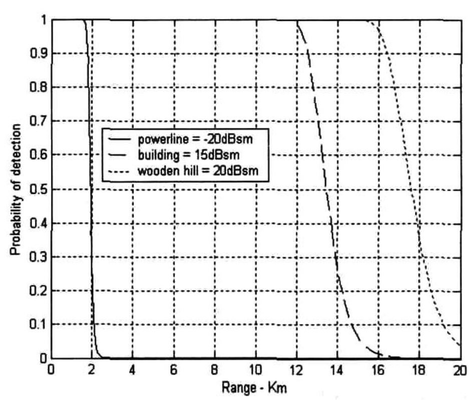

Fig. 3. Detection Prob. vs. Range (Swerling v , LPRF)

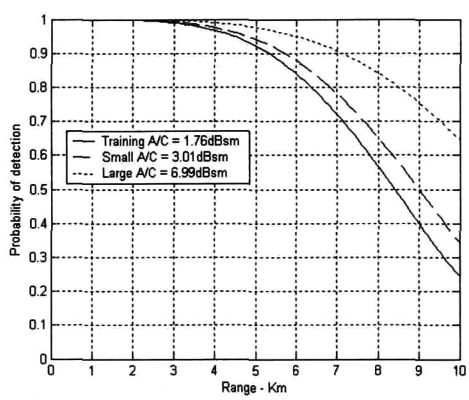

Fig. 4. Detection Prob. vs. Range (Swerling i , LPRF)

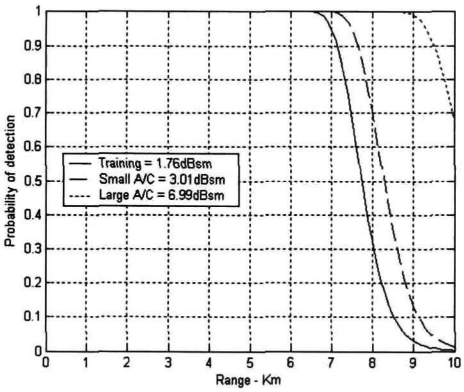

Fig. 5. Detection Prob. vs. Range (Swerling ii, LPRF)

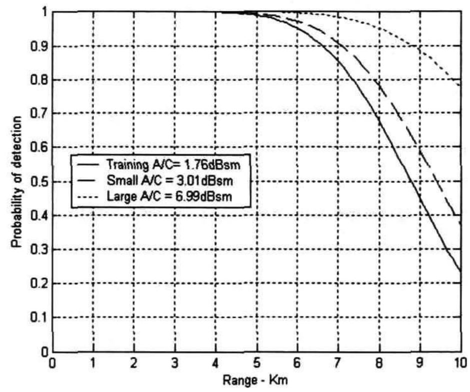

Fig. 6. Detection Prob. vs. Range (Swerling iii, LPRF)

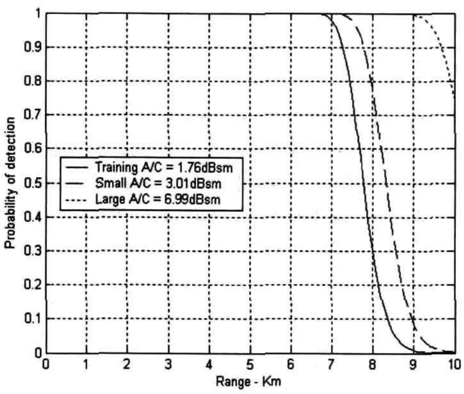

Fig. 7. Detection Prob. vs. Range (Swerling iv, LPRF)

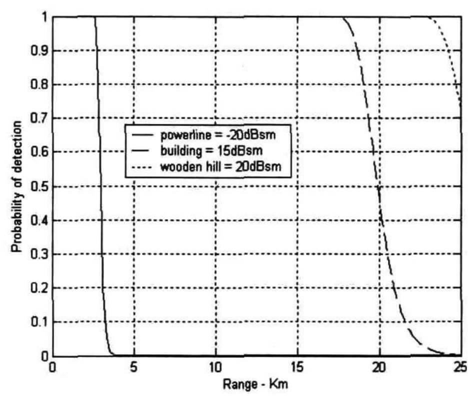

Fig. 8. Detection Prob. vs. Range (Swerling v, HPRF)

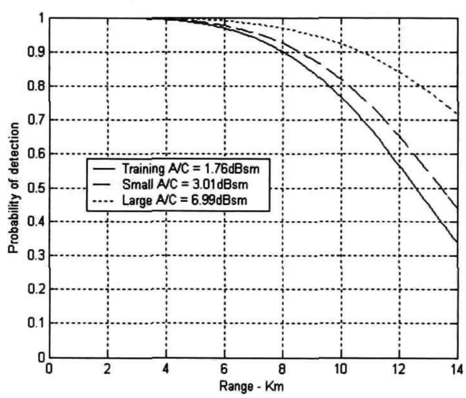

Fig. 9. Detection Prob. vs. Range (Swerling i, HPRF)

aircraft which were not detected in low PRF mode are capable of detection more than 90% as shown in Fig. 8-9. Since that if high PRF more than 15KHz is used for increasing SNR, unambiguous range will be shorter than 10km, high PRF mode of 15KHz is designed to escape range ambiguity.

Collision Avoidance Mode Performance

The Collision avoidance problem is to determine the possibility of collision, and to provide the maneuvering command to the vehicle in the complicated obstacle environments. There are three modes of operations to be conceived: search mode(detect), awareness mode(detect and track) and avoidance mode (maneuvering). The procedure of the collision avoidance is shown in Fig. 10.

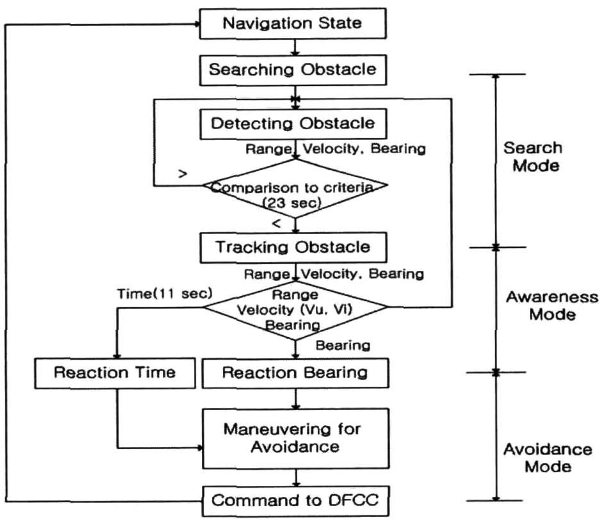

Fig. 10. Concept of Collision Avoidance

In search mode from the normal navigation state, the UAV flies to the pre-programmed destination by navigation system and CAS radar searches the obstacle coming close to own vehicle. Once any objects comes close within the time-to-collision of 23 sec, the search modes is transferred to the awareness mode, which can now react the obstacle by tracking the moving obstacle by updating the vector of the object every scan rate. If the time-to-collision of any closing objects is less than 11sec during the track, the avoidance mode is initiated to maneuver the vehicle. In this case, the potential collision point and safety circle (500ft) are computed and waypoint is set on the safety circle for avoidance maneuvering. UAV maneuvers depending on the avoidance angle, which is computed based on the waypoint and potential collision point. Otherwise, if the threat is removed, then the normal navigation state is returned while searching ant threats. The collision avoidance performance primarily depends on the range, range-rate and bearing in the various flight scenarios.

Formulation for Collision Avoidance Algorithm

The basic collision avoidance algorithm is as follows.

for $t=t_0$: 1(sec) : t_n (Search Mode)

- Coordinates of UAV is

$$X_{uav}(t)=X_{uav}(t_0)+\{V_{uav}\times\cos(\Theta_{uav})\}$$

$$Y_{uav}(t)=Y_{uav}(t_0)+\{V_{uav}\times\sin(\Theta_{uav})\}$$

where V_{uav}=UAV velocity, Θ_{uav}=velocity angle of UAV

- Collision time is

  $T_c(t)=d_r(t)/v_r(t)$

  where $d_r(t)$=range information using radar, $v_r(t)$=range-rate information using radar

if (Tracking Mode based on time-to-collision criteria / $Tc \leq 23$sec)

- Distance between UAV and Safety circle is

  $d_w(t)=sqrt(d'_r(t)^2-r_s^2)$

  where $d'_r(t)$=distance between UAV and predicted collision point

  r_s=safety circle radius(150m)

- Avoidance Angle is

  $angle(t)=asin(r_s/d'_r(t))$

- Avoidance Angular Velocity is

  $av(t)=angle(t)$/avoidance time(11sec)

- Coordinates of waypoint is

  $W_x(t)=X_{uav}(t)+d_w(t)\times\{\cos(90^\circ-angle(t))\}$

  $W_y(t)=Y_{uav}(t)+d_w(t)\times\{\sin(90^\circ-angle(t))\}$

then if (Avoidance Mode / $11sec \geq Tc$ & $Tc>10sec$)

- In the avoidance mode, Coordinates of UAV is

  $X_u(t)_{uav}=X_{uav}(t)+\{V_{uav}\times\cos(\Theta_{uav}-av(t)\}$

  $Y_u(t)_{uav}=Y_{uav}(t)+\{V_{uav}\times\sin(\Theta_{uav}-av(t)\}$

end

end

- Back to search mode

end

Flight Scenario 1

The first scenario is the case where the moving obstacle is closing in the radial direction with the speed of 560km/h whose aspect angle is 0 degree. In this case, since the speed of UAV is 440km/h, the closing speed becomes 1000km/h. When the awareness mode is initiated(time-to-collision of 23sec), the distance between UAV and moving obstacle could be 3.1km. In avoidance mode (time-to-collision of 11sec), the time that moving obstacle comes to potential collision point is 10.5sec and the distance between UAV and waypoint is 1.47km, which is sufficient time for UAV to avoid from the collision risk. As shown in Fig. 11, UAV avoids safely the moving intruder obstacle in the closing direction without collision approach into the safety circle.

It is assumed that the collision avoidance radar information such as range, azimuth, range-rate is accurate. However if there is an error in the radar information, it has an effect on the collision avoidance performance. The minimum distance between UAV and safety circle is analyzed for securing the safety during avoidance maneuvering in the given erroneous information of azimuth and range-rate. It is assumed that the range of azimuth error is equal to radar beam width of 2.5 degree, which is +/- 1.25 degrees centered 0 degree in the avoidance mode. As the simulation result is shown in Figs. 12 and 13, in the given azimuth error information of +1.25 degree, UAV approaches to the potential collision point about 99.327m, which means that UAV approaches into the safety circle about 50.673m and collision risk is very high. On the other hand, in case of given azimuth error of -1.25 degree, the minimum distance between UAV and safety circle during the avoidance mode becomes 204.586m, which means that UAV maneuvered more safely than no-error condition.

In case of given range-rate error of 8m/s, the closing speed becomes 1030km/h and UAV approaches into the safety circle about 40.738m, which means that collision risk is high, as shown in Fig. 14.

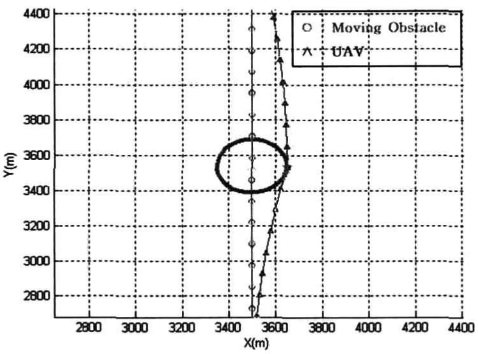

Fig. 11. Trajectory of UAV and Obstacle in the Radial Direction

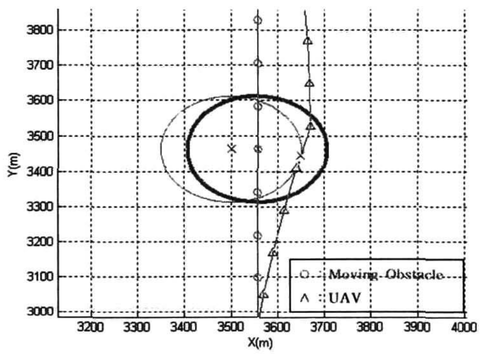

Fig. 12. Trajectory in Azimuth Error : +1.25 Degree

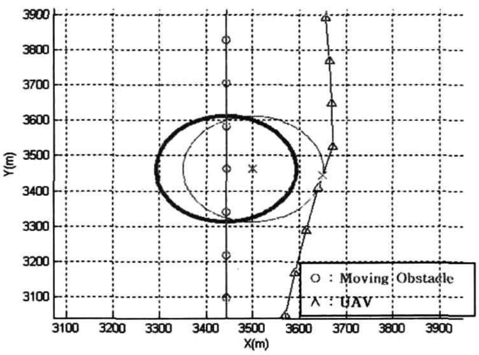

Fig. 13. Trajectory in Azimuth Error : -1.25 Degree

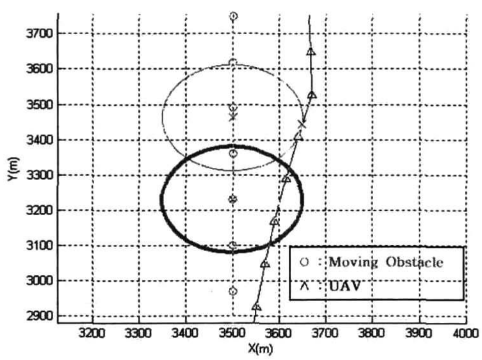

Fig. 14. Trajectory in Velocity Error : 8m/s

Flight Scenario 2

The second flight scenario is the more general case where the moving obstacle is closing in the off-angular direction from 0 to 90 degree. In this simulation, it is assumed that moving obstacle comes close to UAV with aspect angle of 30 degree and speed of 500km/h. Since the time-to-collision

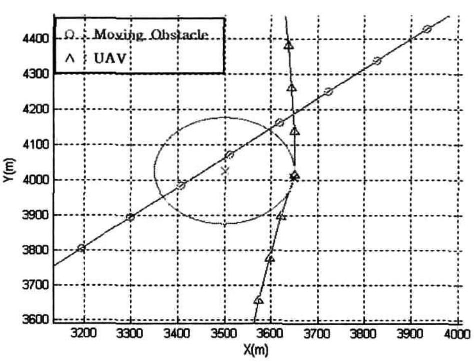

Fig. 15. Trajectory of UAV and Obstacle in the Angle Direction

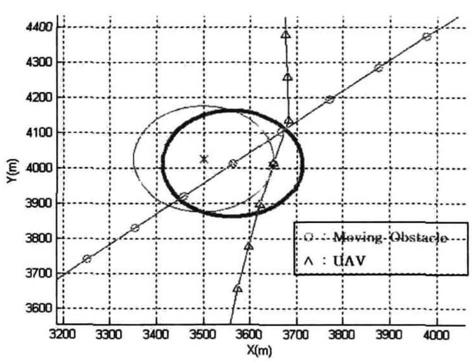

Fig. 16. Trajectory in Azimuth Error : +1.225 Degree

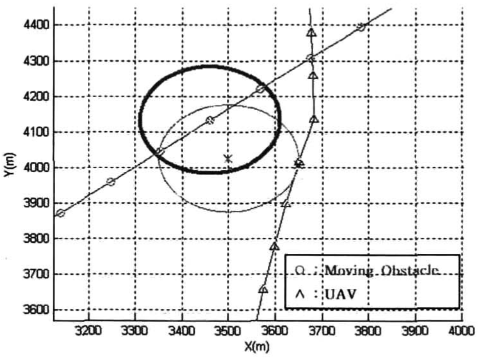

Fig. 17. Trajectory in Azimuth Error : -1.194 Degree

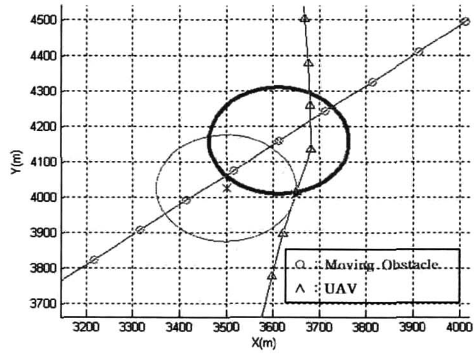

Fig. 18. Trajectory in Velocity Error : -6m/s

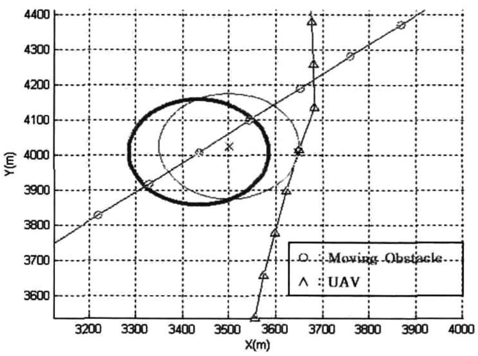

Fig. 19. Trajectory in Velocity Error : +2m/s

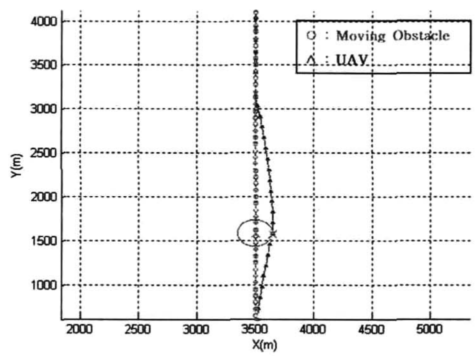

Fig. 20. Trajectory of UAV and Opening Obstacle

is calculated depending on the closing speed, and there is a difference between direction of moving obstacle and closing velocity vector, the potential collision point becomes different from the trajectory of obstacle about 40m. Fig. 15 shows that UAV avoids safely the moving intruder obstacle with off-angle.

The azimuth errors are assumed from -1.194 degree to +1.225 degree centered 0 degree. In case of azimuth error of +1.225 degree, the minimum distance between UAV and potential collision point becomes 88.193m, as shown in Figs. 16-17. The other hand, in case of -1.194 degree, the minimum distance becomes 221.909m. Fig. 18-19 show the simulation results for given range-rate error, which is from -6m/s to +2m/s. If the range-rate error is beyond 2m/s and/or below -6m/s, collision avoidance can not be guaranteed. In case of range-rate error of -6m/s, the minimum distance between UAV and potential collision point is 72.569m. On the other hand, in case of +2m/s, the minimum distance becomes 215.676m.

Flight Scenario 3

The third scenario is the case where the obstacle vehicle flies to the opening direction, but own vehicle moves faster than the obstacle speed. In this case, there is a collision possibility in only case where the speed of own vehicle is faster than that of the opening obstacle. In this simulation, it is assumed that the UAV speed is 440km/h and the speed of moving obstacle with opening direction is 270km/h. Fig. 20 shows the simulation result.

Flight Scenario 4

The fourth scenario is the case where the stationary obstacles such as tower or hill are within the threat distance. In case of stationary obstacle, due to the zero speed of obstacle, collision can be avoided if the range and azimuth information of the obstacle is available. The distance from UAV to obstacle becomes to 2.8km with the UAV speed of 440km/h at the awareness mode, which means that once the collision avoidance radar secure the detection range of 2.8km, collision avoidance will be feasible. Avoidance maneuvering initiates at the distance of 1.3km from obstacle. Fig. 21 shows the simulation result, which is assumed the stationary obstacle as a circle with radius of 100m. Fig. 22-23 show the simulation result for given azimuth errors, which are from -1.23 degree to +1.23 degree. In case of azimuth error of +1.23 degree, the minimum distance between UAV and potential collision point is 120.391m. The other hand, in case of -1.23 degree, the minimum distance becomes 171.26m.

Performance Evaluation and Discussion

From the simulation results described in case of erroneous radar information of azimuth and range-rate, UAV could moves into safety zone about 50m, which means that collision risk between UAV and obstacle is very high. Margin boundary circle which is extended from the safety circle is desirable, and new waypoint is set on this margin boundary circle to secure the safety for given erroneous information.

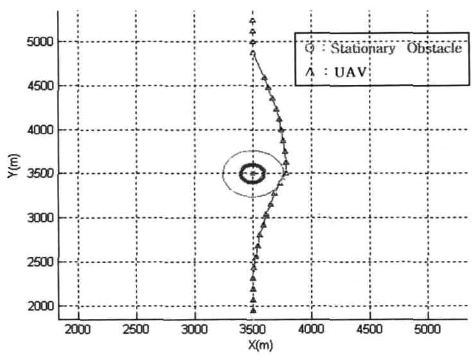

Fig. 21. Trajectory of UAV and Stationary Obstacle

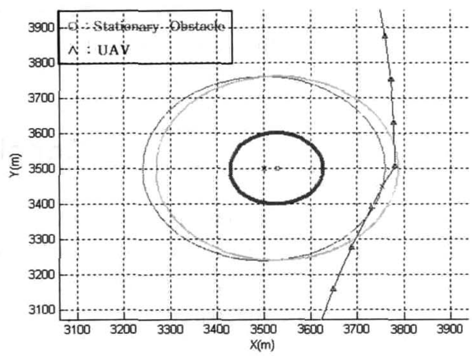

Fig. 22. Trajectory in Azimuth Error : +1.23 Degree

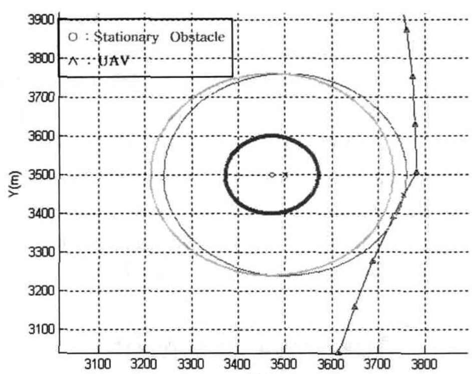

Fig. 23. Trajectory in Azimuth Error : -1.23 Degree

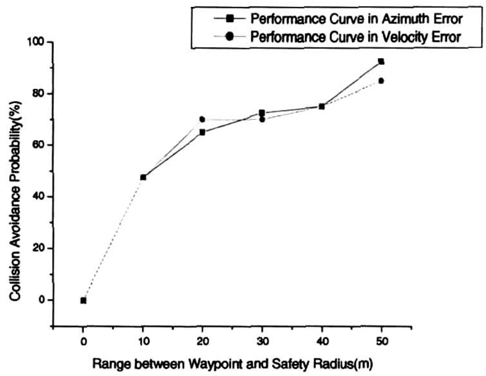

Fig. 24. Collision Avoidance Performance - Scenario 1

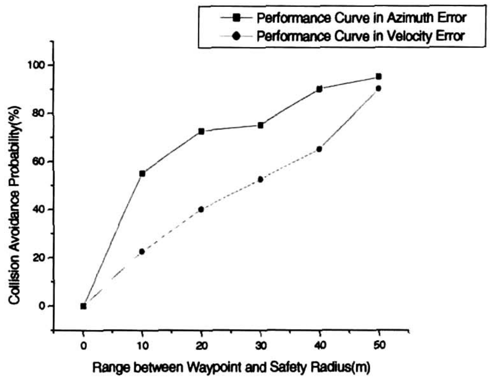

Fig. 25. Collision Avoidance Performance - Scenario 2

Collision avoidance performance according to size of margin boundary circle is evaluated in case of azimuth error corresponding to radar beam width. In this case, the range-rate error is randomly generated from 0m/s to 8m/s.

In case that waypoint is set on the margin boundary circle which is extended about 50m from the safety circle, the probability of collision avoidance is over 85% for the given erroneous radar information (Fig. 24-25).

Conclusions

Due to the inherent nature of the low flying vehicle, obstacle detection along the path is a fundamental requirement to avoid the collision against stationary and/or moving target obstacles. In this paper, the critical sensor characteristic for obstacle awareness and avoidance is assessed with the compliance of the equivalent level of safety regulation. Based on the assessment of the obstacle awareness and collision avoidance sensor, the small-sized, light-weighted radar sensor is proposed for the suitable candidate in meeting with the system requirement as well as operational requirement of smart unmanned vehicle. The conceptual radar design result is also presented with the design parameters and the radar detection and avoidance procedure are simulated with the probability of obstacle detection and the avoidance scenarios. As a result of performance assessment for obstacle detection performance, probability of detection is more than 90% at the given required detection range. The performance of collision avoidance mode is also simulated based on the various radar range and range-rate data in the four different flight scenarios. The simulation results shows that in case of radar error data, the safety margin boundary is well designed for securing the safety of UAV, and the more than 85 % of probability of collision avoidance can be achieved within the requirements. However, it is desirable to approach to the synthetic method by combining the advantages of the non-cooperative radar sensor as well as cooperative TCAS and ADS-B to efficiently increase the probability of collision avoidance for the non-stationary moving aircrafts as well as stationary obstacles in the low-flying UAV.

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References

1. Tarak Gandhi and et al., 2001, "Detection of Obstacles in the Flight Path of an Aircraft", IEEE Tr., AES vol. 39, no. 1, pp. 176-191.

2. Anthony Mangogno and et al., 2001, "Development of a Helicopter Obstacle Detection and Air Data", IEEE 20th Digital Avionics Conference, vol. 1, pp. 1-18.

3. B. Kumar and D. Ghose, 2001, "Radar-Assisted Collision Avoidance /Guidance Strategy for Planar Flight", IEEE Tr. AES. Vol. 37, No. 1, pp. 77-90.

4. Russel Wolfe, 2003, "Non-Cooperative Collision Avoidance Flight Test Results & Analysis", European UVS Tech 2003 Conference.

5. Williamson T., Spencer N.A., 1989, "Development and operation of the Traffic Alert and Collision Avoidance System (TCAS)", Proceedings of the IEEE , vol. 77 , pp. 1735-1744.

6. Young K Kwag, 2004, "Obstacle Awareness and Collision Avoidance Radar sensor System for Low-Altitude Flying Smart UAV", the Proceeding of IEEE the 23rd DASC, Salt Lake City, Oct. 2004.

7. Jung Wan Kang, 2005, "Collision Avoidance Radar Sensor Design and Performance Analysis for UAV", MS Thesis, School of Avionics and Telecom.. Eng., HanKuk Aviation University, Feb. 2005.

8. Swerling P.,1997, "Radar Probability of Detection for Some Additional Fluctuating Target Cases", IEEE, Aerospce and Electronic Systems, vol. 33, pp. 698-709.

9. William Morchin, 1993, "Radar Engineer's Source Book", Artech House.