Applying Multisensor Information Fusion Technology to Develop an UAV Aircraft with Collision Avoidance Model

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Abstract

This paper presents a multisensor information fusion technological application for the development of an improved version of unmanned air vehicles (UAV) where almost 100% of flight control is accomplished by the computer software.

The UAV, or drone, has been employed by the U.S. government for support of military action in the battlefields of the Iraq and Afghanistan wars. The UAVs perform air, land, and sea surveillance without risking the life of a pilot. Lately, the Iranian government claims to have captured a U.S. UAV inside their territory. Continued development of the UAV is critical to the support of the war fighter.

In this paper, a new avionic architecture and algorithmic software model for the UAV is introduced. What is new about this is the application of the multisensor information fusion technology. Particularly, the avionics architecture of a master controller including new algorithms for air traffic and collision avoidance (TCAS). This improved approach to UAV control can detect, track, and positively identify multiple targets in the multisensor environment. Multisensor information fusion technology provides a significant advantage over traditional control technology for the UAV.

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Figure 1 Picture courtesy of Public Broadcasting's NOVA series

Introduction

The objective of this paper is to explore a new improved architectural design for the UAV or drone. Such aircraft, flown without pilots, have been in use for more than a decade. The US government has heavily deployed UAVs to support the military in the Iraq and Afghan wars. The UAV is primarily used for reconnaissance and surveillance, taking real-time pictures, and sending the images back to the military command/control center.

With the proposed level of automation, this new UAV only needs a mission commander to provide high-level direction. The UAV can fly safely at all times and is completely guided by advance computer software based on the multiple target and multisensor information fusion technology. The most important component on-board the UAV is the master controller with GPS receiver. It guides the UAV based on the GPS system, from start-of-flight to end-of-flight at required destination and return to earth phase. The master controller with the help from the GPS system is constantly communicating with the following embedded advanced computer software modules:

1) Multisensor and target acquisition module
2) Extended Kalman Tracker module
3) Multisensor Correlation Module
4) Multisensor Information Fusion
5) Traffic Alert and Collision Avoidance Module

This newly proposed UAV with traffic alert and collision avoidance module is a completely new, and technically challenging, development stage. As the electronic and computer technology improve, multisensor information fusion technology, particularly the multiple target tracker algorithm improve, the future UAV with traffic alert collision avoidance module will become reality.

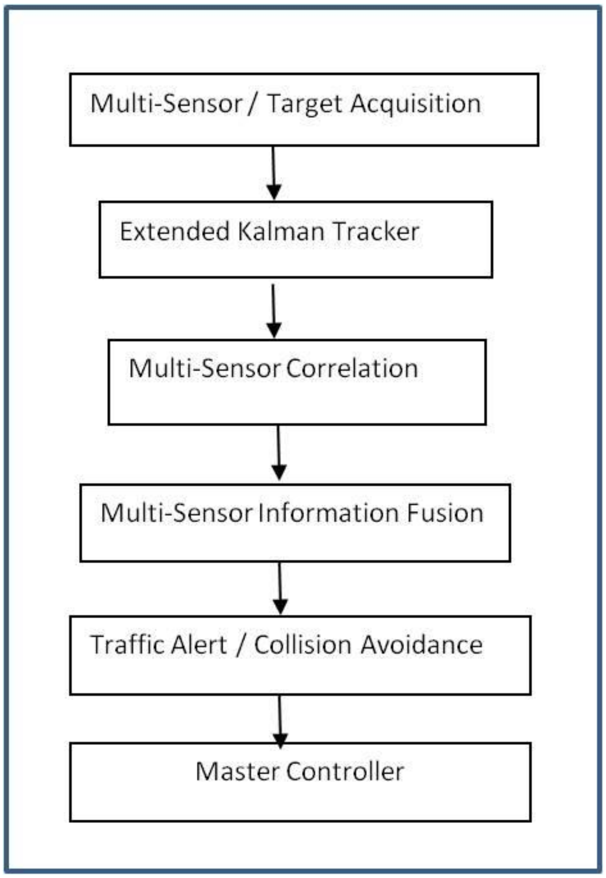

Figure 2 Functional Flow

Multisensor Target Acquistion Module

The multisensor target acquisition module employs a GPS receiver and advanced sensors such as APG radar, CNI and EW sensor, to keep track of own-ship and targets of interest. The multisensor module provides sensor information to the Extended Kalman Tracker module. The sensor information is then used to communicate with the traffic collision module and the master control module, so the unmanned aerial vehicle can fly safely without a pilot in the loop.

Figure 3 From wikipedia.org/wiki/Global Position System

GPS is the space based navigation satellite system, which provides location, and time information at any given time. From anywhere on earth, there is an unobstructed line of sight to four or more GPS satellites. The system provides critical capabilities to military, civil, and commercial users around the world. It is maintained by the United States government and is freely accessible to anyone with a GPS receiver.

Below is a visual example of the GPS constellation in motion with the Earth rotating. Notice how the number of *satellites in view* from any given point on the Earth's surface, in this example at 45°N, changes with time.

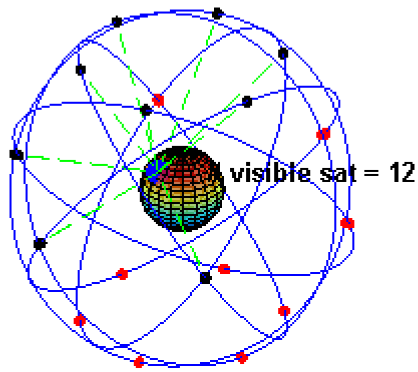

Figure 4 Constellation of GPS satellites

Navigation equations

[Leon, 2006]

The GPS receiver uses messages received from satellites to determine the satellite positions and time sent. The *x, y,* and *z* components of satellite position and the time sent are designated as [x_i, y_i, z_i, t_i] where the subscript *i* denotes the satellite and has the value 1, 2, ..., *n*, where $n \geq 4$. When the time of message reception indicated by the on-board clock is $\tilde{t}_\text{r}$, the true reception time is $\tilde{t}_\text{r} + b$ where b is receiver's clock bias (i.e., clock delay). The message's transit time is $\tilde{t}_\text{r} + b - t_i$. Assuming the message traveled at the speed of light, c the distance traveled is $\left(\tilde{t}_\text{r} + b - t_i\right) c$. Knowing the distance from receiver to satellite and the satellite's position implies that the receiver is on the surface of a sphere centered at the satellite's position with radius equal to this distance. Thus, the receiver is at or near the intersection of the surfaces of the spheres if it receives signals from more than one satellite. In the ideal case of no errors, the receiver is at the intersection of the surfaces of the spheres.

The clock error or bias, *b*, is the amount that the receiver's clock is off. The receiver has four unknowns, the three components of GPS receiver position and the clock bias [*x, y, z, and b*]. The equations of the sphere surfaces are given by:

$$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = \left([\tilde{t}_\text{r} + b - t_i]c\right)^2, \; i = 1, 2, \dots, n$$

Or in terms of *pseudo ranges*, $p_i = \left(\tilde{t}_\text{r} - t_i\right) c$ as

$$p_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} - bc, \; i = 1, 2, ..., n.$$

These equations can be solved by algebraic or numerical methods.

The Extended Kalman Tracker Model

[Sorenson, 1985] & [Jeun, Hung, Younker, 2003]

This target tracker model is responsible for taking input information from the sensor and target models, and tracking own-ship and the targets of interest at any given time.

Mathematically, the Extended Kalman Tracker model can be defined as follows:

$$X_k = \varphi_k \times X_{k-1} + U$$

B. Propagating the state covariance matrix (U):

$$P_k = \varphi_k \times P_{k-1} \times {\varphi_k}^T + Q$$

C. Kalman gain matrix (U):

$$K = P_K \ X \ H_t \ X \ inv\{ H \ X \ P_k X H_t + R\}$$

D. Gating algorithm (U):

$$G = (Z - H * X_k)^t * \{ H * P * H^T + R\}^{-1} * (Z - H * X_k)$$

E. Updated state covariance matrix (U):

$$P_{k+1} = P_k * (I - G * H)$$

F. Updated state vector (U):

$$X_{k+1} = X_k + G * (Z - H * X_k)$$

where:
U = Noise Vector
φ_k= Transition Matrix
Q = Noise Covariance Matrix
R = Measurement Noise Matrix
Xk = State Vector at time k
Pk = State Covariance Matrix at time k
H = Jacobian Matrix
G = Gating Matrix
K = Kalman Gain Matrix
Z = Measurement vector

The Extended Kalman Tracker is one of the most widely used trackers. Track accuracy is very good. However, as equations C, D, and E indicate, matrix inversion is required in every calculation for each sensor update. Matrix inversion is intensive processing and will slow down total track processing and degrade track accuracy.

Multisensor Correlation Module

The Multisensor Correlation Module is responsible for correlating all target of interest. It takes input from the Extended Kalman Tracker, and outputs the results of the correlated targets of interest to the Multisensor Information Fusion Probability Module (which then calculates the fused probability or measurement of strength of the detected targets).

The Multisensor Correlation module can be expressed mathematically as follows:

Let:
X ={*x1, x2, x3,……………xn*} be the feature vector of an object
Y ={*y1, y2, y3,…………….yn*} be the feature vector of another object

The correlation coefficient between the two feature vectors X and Y is:

R(X, Y) = X●Y / (X●X - X●Y + Y●Y) [Jeun, 1997]

Where:
X●X is the dot product of X
X●Y is the dot product of X and Y
Y●Y is the dot product of Y

Decision rules for the multisensor correlation module are:

(1) If 0.95 <= R(X,Y) <=1.0,
then X and Y are most likely correlated

(2) If 0.0 <= R(X<Y) <=0.95,
then X and Y are most likely NOT correlated.

The boundary condition, 0.95, is selected based on the feature vector element's precision.

Multisensor Information Fusion Probability Model

This probability model is used to calculate the fused probability of all detected targets of interest. Fused probability is defined as the probability of the target being in the multisensor environment. For example, suppose there are two targets reported by three sensors, such as radar, communication navigation and identification (CNI), and electronic warfare (EW). The multisensor information fusion probability model will calculate the probabilities for the two targets as

$P(T_1 / S_1, S_2, S_3) = 0.3$

That is, the probability of target T_1 is 0.3 in the three-sensor environment.

$P(T_2 / S_1, S_2, S_3) = 0.7$

That is, the probability of target T_2 is 0.7 in the three-sensor environment.

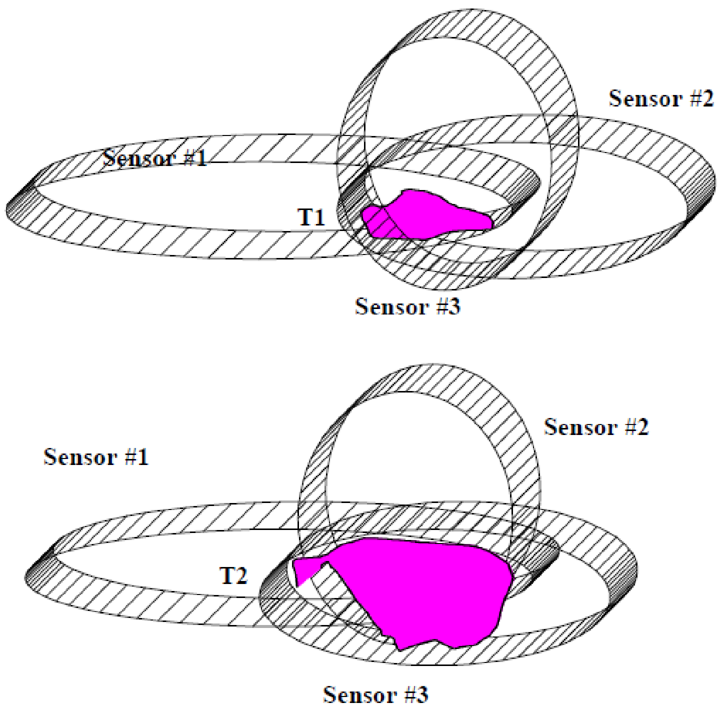

Figure 5 Venn Diagram of Probability

The fused target probability for the multisensor and multiple targets can be expressed as [Hall, 1992]:

$$P\left(\frac{T_k}{S_1.S_2.S_3 \dots S_n}\right) = \frac{\left\{P\left(\frac{S_1}{T_K}\right) \times P\left(\frac{S_2}{T_K}\right) \times P\left(\frac{S_3}{T_K}\right) \times \dots P\left(\frac{S_n}{T_K}\right)\right\}}{\left\{\sum_{i=1}^{n} \left[P\left(\frac{S_1}{T_i}\right) \times P\left(\frac{S_2}{T_i}\right) \times \dots P\left(\frac{S_n}{T_i}\right)\right]\right\}}$$

Where:

$P\left(\frac{T_k}{S1.S2.S3...Sn}\right)$ is the probability of target T_k in the multisensor environment.

For the single sensor with multiple targets, the fused target probability reduces to the following:

$$P\left(\frac{T_k}{S}\right) = \frac{\left\{P\left(\frac{S}{T_K}\right)\right\}}{\left\{\sum_{i=1}^{n} \left[P\left(\frac{S}{T_i}\right)\right]\right\}}$$ [Jeun, 1979]

This expression is exactly the same as the probability of association.

Traffic Alert and Collision Avoidance Module

[Nahi, 1969]

The Traffic Avoidance Module is the new feature of this UAV avionics architecture. It receives own-ship and target feature pattern vectors from the Multisensor Information Fusion Probability Model. Here in this traffic voidance module, the critical target track information is used to estimate the exact location, speed, and track of targets. With that information, looking ahead in time, possible collisions can be predicted. This life and death collision information will output to the UAV Master Control Module and the Master controller can take immediately action to avoiding the collision.

The major function of the traffic avoidance module is to estimate the possible collision parameters, such as the location, time and speed that the collision may happen. Here two new techniques are proposed; one is the analytical method from the theory of estimation, and the other is a geometrical method. Each method has its own distinct merits, depends on what detailed information is available from the Extended Kalman Tracker module.

Analytical Method from the Theory of Estimation

The Traffic Avoidance Module receives more then thirty observation points in each frame (in general, one frame is 40 milliseconds) from the Extended Kalman tracker module. It then applies the so-called "least squares" method to the observation points to obtain the algebraic functions for the targets. Say, Y1(t) is own-ship and the target of interest is Y2(t). Then solve the two algebraic equations: Y1(t) for the own-ship, and Y2(t) for the target of interest.

For the actual value of t, substitute the value of t of either Y1(t) or Y2(t) for the value of Y1 or Y2. The point (y1, t) or point of (y2, t) is the possible location at which the own-ship and the target of interest will collide with each other. After the location of collision is determined, the time and speed of collision can be solved by simple physics techniques.

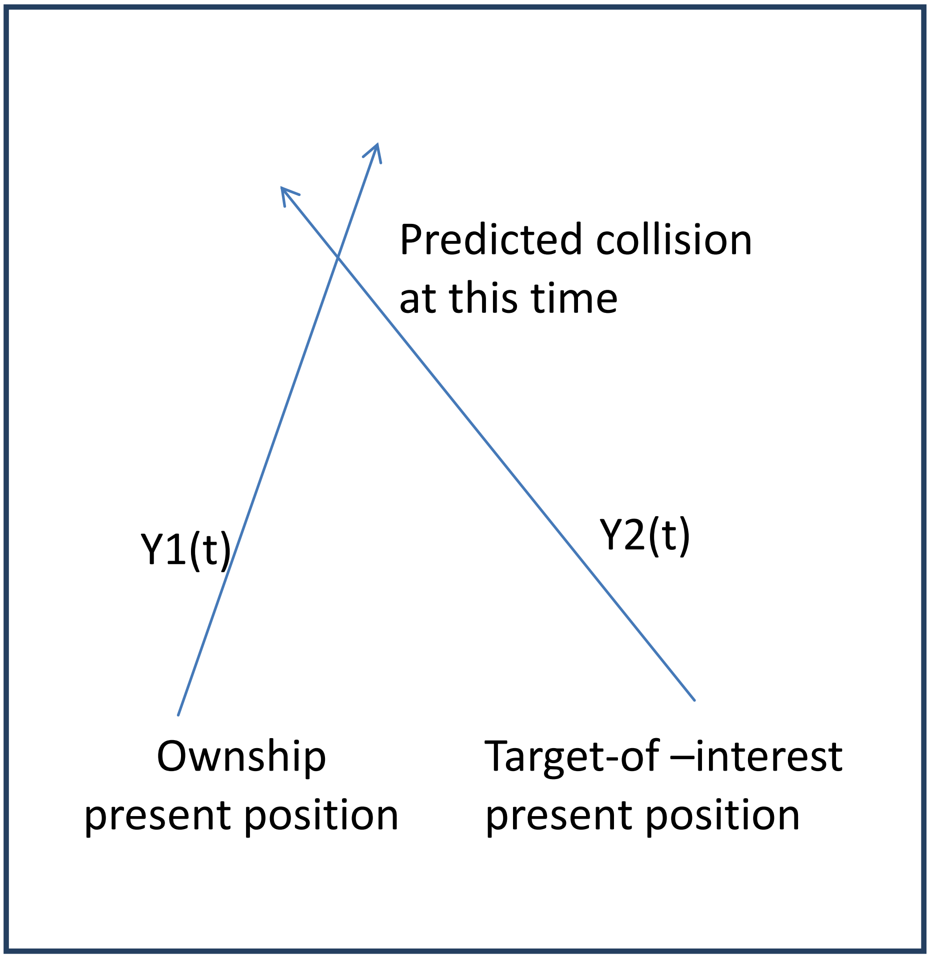

Figure 6 Analytical Method of prediction

Geometrical Method

This method applies a graphical solution technique to the heading and velocity vector for own-ship. Say, for example, HD1 and V1 are the heading and velocity vectors for own-ship. Similarly, say, HD2 and V2 are the heading and velocity vectors for a target of interest. Denote the length between the north-referenced point of HD1, and V1, by L1. Similarly, denote the length between the north-referenced point of HD2, and V2, by L2.

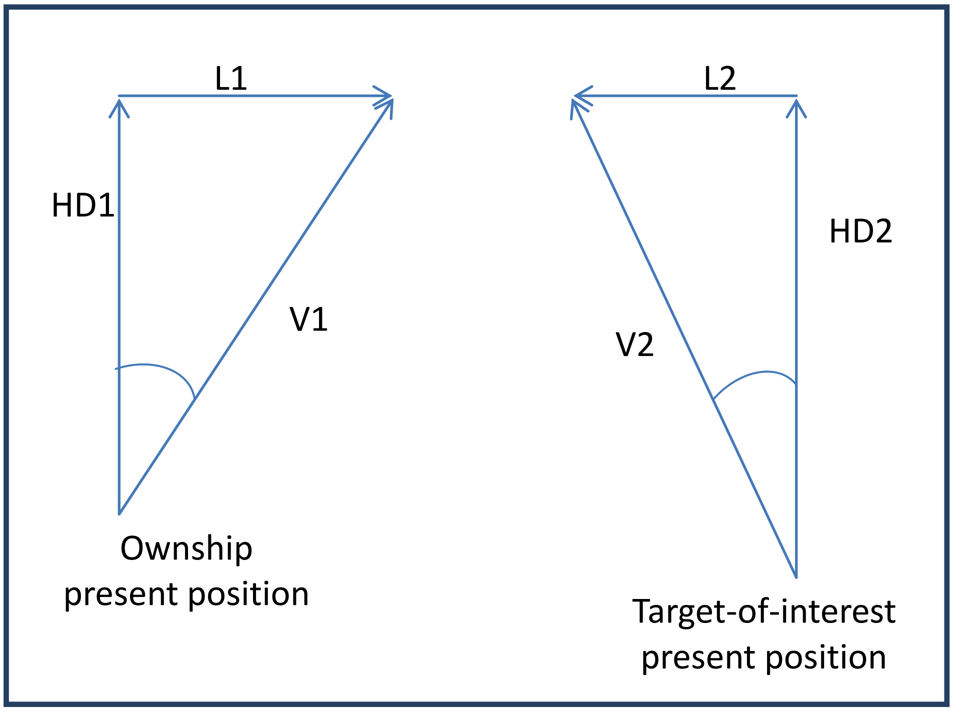

Figure 7 Geometrical Method

From the above diagram, you can see the point at which own-ship and the target of interest will collide with each other. That is, when L1 equals L2. That is mathematically:

$\sin(\alpha) = L1 / V1$ ....(1)

And

$\sin(\beta) = L2 / V2$ ....(2)

From (1), $L1 = V1 * \sin(\alpha)$ ....(3)

And

From (2), $L2 = V2 * \sin(\beta)$ ....(4)

The values of L1, V1, and V2 are known from the Extended Kalman Tracker, and the angle β is unknown. If L1 and L2 were equal, then (3) and (4) would yield the following equation:

$V1 * \sin(\alpha) = V2 * \sin(\beta)$

And $\sin(\beta) = [\, V1 * \sin(\alpha) \,] / V2$

Therefore, $\beta = \text{Sin}^{-1}\{ [V1 * \text{Sin}(\alpha) / V2 \}$

β is the angle at which the own-ship and the target of interest will collide with each other. The angle value would be sent to the Master Control Module from the Traffic Avoidance Module. The Master Controller Module will then send commands to take action to redirect own-ship (the UAV) to avoid a collision with the target of interest.

Example

Following is a simulated solution for the determination of location at which two aircraft could collide with each other. The estimation of the point of collision is essential for avoidance of the collision.

A. Taking a series of points from the Extended Kalman Tracker for own aircraft and target aircraft and using "least square method", we obtain an algebraic equation for the velocity vector for own aircraft and the target aircraft as following:

   Y = X (equation for the velocity vector of own aircraft)----------(1)

   Y = 16 – X (equation for the velocity vector of the target aircraft)---------(2)

B. To estimate the interception point between these two equations as the point of collision we set equation (1) equal to equation (2) as follows

   X = 16 – X --(3)

   That is 2X = 16

   Finally X = 8

   Now substituting X = 8 into equation (1) or equation (2) , we have

   Y = 16 – X

   Y = 16 – 8

   Y = 8

C. The required solution for the point of collision between these two aircrafts is P(8,8). This is just a simulated solution to demonstrate our concept of collision avoidance of between two aircraft.

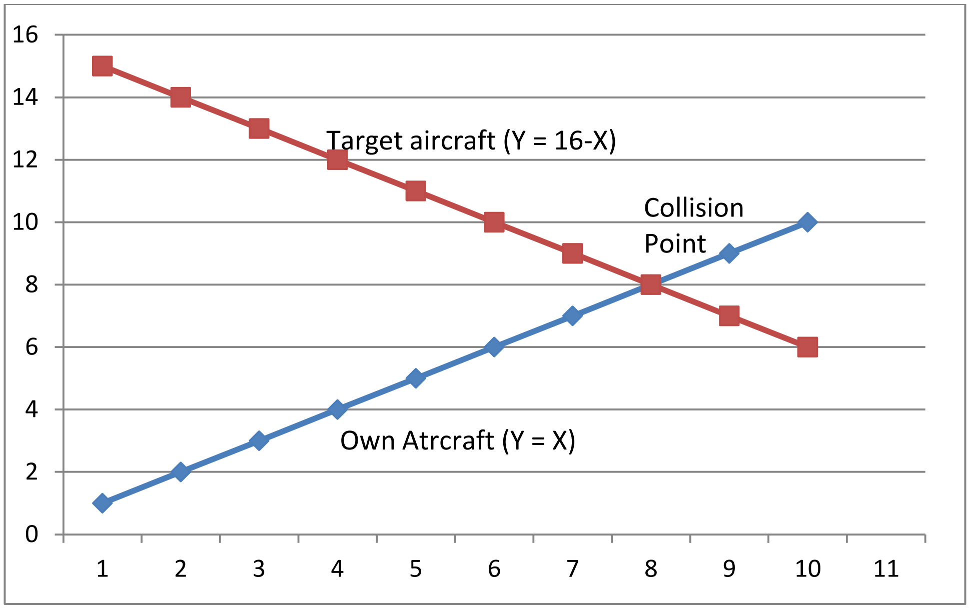

Figure 8 Predicted Collision

Master Controller Module

The Master Controller module in this UAV avionics architecture acts like an intelligent human pilot guiding the UAV safely through its assigned mission. The newly proposed UAV with Traffic Alert and Collision Avoidance Module is 100% controlled and guided by the computer software modules.

The Master Controller is the master of all modules onboard the UAV. Equipped with GPS receiver, it receives from the GPS satellites. It provides navigation information, such as target and own-ship location information from the satellite navigation system. At the same time, the Master Controller is communicating and monitoring all other computer software modules.

The software modules onboard the UAV are:

1) Multisensor and Target Acquisition Module

2) Multisensor and Multiple Target Tracker

3) Multisensor Correlation Module

4) Multisensor Information Fusion Probability Module

5) Traffic and Collision Avoidance Module

The most important responsibility of the Master Controller is guiding the UAV navigating through the earth safely. The Traffic alert and collision avoidance module provides target location information and target parameters such as heading, velocity vector, target feature vector, and time of possible collision to the Master Controller. As soon as the collision target parameters reach the Master Controller, the warning signal is sent through the UAV. Immediately the Master Controller approves all actions to avoid the possible target collision. Location and time at which the UAV and Target of interest will collide are calculated by the traffic alert and collision avoidance module. The master controller takes immediate action before the collision occurs. The new UAV is guided by the Master Controller, Traffic Alert and Collision Avoidance Module, other onboard computer software modules, and the GPS system. It can fly freely anywhere on earth without a human pilot.

Conclusions

The current proposed UAV is in the exploration phase. The onboard master controller is 100% guided by advanced embedded computer software, and communicates with the advanced GPS System, that includes the 24 navigation satellites orbiting the earth with unobstructed view of at least 4 satellites, which will provide target location information to the UAV anywhere on earth and at anytime. In addition, the newly proposed UAV is guided with a multisensor and multiple target tracker. This tracker is the most advanced target tracker in the field. It uses the Extended Kalman tracker that has been implemented on advanced fighter jets, and airborne surveillance aircraft. Therefore, the authors firmly believed that the new UAV with traffic alert and collision avoidance module, will become a new standard architecture for UAVs.

Further in the future, this same multisensor information fusion technology with advanced GPS system could also be applied to guiding driverless automobiles. Future automobiles could be on the road with improved safety due to computer guidance being more reliable than human drivers. This is a very important next step considering the rapidly aging population of developed countries.

When nanotechnology is combined with multisensor information fusion technology and the advanced GPS system, this concept can be applied to development of future unmanned airborne vehicles (UAV). The size of the future UAV will be smaller which will further reduce detection in the air and save on fuel.

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