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IFAC PapersOnLine 50-1 (2017) 15032–15037

Research on Intercepting Strategy of Multiple Kill Vehicle in Midcourse Defense Based on Multi-Sensors Fusion Method

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Abstract: The multiple kill vehicle (MKV) interceptor consists of a carrier vehicle and some small kill vehicles which can intercept multiple targets independently. According to the mission of midcourse interception for multiple warheads of long-range ballistic missile, this paper focused on the design and optimization of cooperative detection and guidance strategy. Based on multi-sensors fusion technology, the method of high-accuracy position measurement and view expansion of infrared sensors are proposed. The terminal guidance law is analyzed based on the data obtained by the methods. A digital real-time simulation system is developed to verify the feasibility of the method.

Keywords: Multiple Kill Vehicle, Midcourse Missile Interception, Cooperative Detection, Data Fusion, Guidance

1. INTRODUCTION

During the flight of a ballistic missile, the phase when flying out of the atmosphere is called midcourse phase, which takes up about 80-90% time of the whole course. The missile flies by inertia with the engine turned off during the midcourse phase. Since the flight in midcourse phase is relatively smooth and steady and has a long duration, it is easier for the defenders to predict the ballistic trajectory. So midcourse interception is the most efficient solution, which has drawn attention of world's major military power.

However, modern multiple independently targetable reentry vehicle (MIRV) contains several warheads, which will be released at midcourse phase to attack a group of different targets. Furthermore, it may use decoys whose infrared characteristic is very similar to real warheads to increase the difficulty of target identification. Therefore, numerous interceptors are needed to counter the individual target.

U.S. missile defense agency started researching a new kind of intercepting weapon called Multiple Kill Vehicle (MKV) at the beginning of 21st century. It consists of a carrier vehicle and several small, lightweight, and lethal kill vehicles that can intercept targets independently. One or more MKVs can be assigned to intercept all credible targets within a threat cluster when discrimination is challenging. It has the potential to solve many of the most difficult countermeasure challenges.

In this paper, the intercepting strategy and procedure are analyzed. The design and optimization of cooperative detection and guidance strategy are presented. A high-accuracy position measurement method and a sensors' view expansion method are proposed. This article developed a 3D simulation system, and proved the feasibility of the method.

2. RESEARCH ON INTERCEPTING STRATEGY

2.1 Review of Tactical Approaches

There have been continuous researches on the theoretical and technical group intercepting problems these years. The approaches such as "MEDUSA" (Peglow, 1994), "SWARM" (Strickland et al., 1997), "Genius Sand" (Ledebuhr et al., 2002), "MKV-L" (Colvin et al., 2013) and "MKV-R" (Leal et al., 2009) have been proposed.

1) MEDUSA Project

Lawrence Livermore National Laboratory Directed Research and Development Initiative proposed the MEDUSA concept in 1992, which incorporates the use of small, semi-autonomous kill vehicles aboard a missile. Approximately 24 KVs with a sustainer are packaged aboard the PAC and SM2/4 missile systems as an integrated part of the warhead section, with no weight increase for the missile.

The result of the research shows that the concept of intercepting a fractionated threat from a tactical ballistic missile is potentially feasible and would have very high payoff for the defense.

2) SWARM

SWARM is a midcourse multiple kill vehicle concept proposed by U.S. Army Space & Strategic Defense Command in 1997. The approach intended to use hundreds of high

10.1016/j.ifacol.2017.08.2514

performance, low cost kill vehicles having a very small size and weight. The SWARM concept is envisioned to be compatible with the concept of operations of existing or planned interceptor systems such as the THAAD.

3) Genius Sand

Lawrence Livermore National Laboratory proposed another intercepting approach termed Genius Sand(GS) in 2002. They designed to deploy a net of 10 or more GS Miniature kill vehicles weighing 3 to 5 kg each to predict the intercept points. The points would cover the complete volume in space and thus the kill probability is increased. The Miniature kill vehicles offer new capabilities for boost phase intercept missions, as well as midcourse intercepts and the defeat of advanced countermeasures.

4) MKV-L

MKV-L was envisioned in early 2000s by Lockheed Martin Space Systems Company, which consists of a carrier vehicle (CV) with on board sensors and 16 small kill vehicles (KV). The CV assesses the threat set, deploys and assigns the KVs and manages the engagement. The KVs perform threat analysis and interceptions. Each vehicle has its own divert and attitude control component and seeker, thus the probability of interception is significantly increased.

During an engagement with the enemy, the divert and attitude control component will maneuver the CV, with its bandolier of small KVs, onto the path of the inbound threat complex. With the enemy in its sight, the CV dispenses the KVs, guiding them to destroy their designated targets.

5) MKV-R

MKV-R was conducted by Raytheon Company. It consists of several identical kill vehicles with the same capabilities and flexibility. One kill vehicle serves as the engagement manager by communicating battlespace information to the system, simultaneously assigning targets and providing kill assessment. All kill vehicles have the same capability to autonomously track and intercept threats with hit-to-kill accuracy, providing redundancy and eliminating the risk of single point failure.

2.2 Time of KVs' Release

Among the approaches above, MKV-L and MKV-R are relatively mature in feasibility under the current circumstance. When they get into implementation, the releasing time of KVs should be emphatically considered. There are mainly two ways. The first one is dispensing the KVs before finding the targets, so that the KVs will fly around the CV. Once the targets are visible to the detection sensors on CV, there will be enough time to guide the KVs to the targets. The other one is releasing the KVs after targets are detected by CV. Both methods have advantages and disadvantages. The former has a more flexible response capacity, but more fuels are needed from KVs. The latter is more fuel-efficient which helps to the miniaturized design, but better maneuverability is needed when the detection range of CV is limited. So the requirements for divert and attitude control motor is much higher.

2.3 Target Assignment

During an interception of MKV, target assignment should be made by the CV or manager KV based on the track and identification result. The characteristics of targets should be analyzed at first. Then, threat assessment of each target including all warheads and decoys should be made. Combined with the quantity, position and maneuverability of each KV, assign the KVs and guide them to finish the intercept. The fatal problems in target assignment are how to make the characteristics analysis and threat assessment.

Most MKV systems are equipped with infrared seekers. The acquisition of targets' characteristics is by the change of temperature on target, including heat transfer process such as direct and indirect solar radiation, radiation from the earth and radiation from space. The mass and specific heat capacity of decoys are usually less than real warheads. Therefore, the changing rate of temperature of decoys is greater than that of real warheads. Furthermore, the motion state's difference between before and after KVs' releasing such as the change of position and velocity can be used to identify the targets to some extent base on the principle of conservation of momentum.

2.4 Intercepting Constraints

There are many constraints in the MKV group including CV and KVs as a whole system during the interception, which should be carefully considered when designing the intercepting strategy.

1) Energy

The kill vehicle is designed in miniaturization. Take the KV in MKV-L project as an example. The size of KV is similar to a coffee can weighing about 10 pounds (4.5 kg). Hence, the amount of fuel it can take is quite limited, which will directly affect the design of midcourse and terminal guidance law, the releasing time and the dispensing method. In order to achieve the high guidance accuracy of destroying the target, the limit of the total amount of energy should be fully considered during overall intercept designing phase.

2) Maneuverability

The kill vehicle is controlled by reaction force. A typical KV is equipped with 4 divert thrusters to adjust the trajectory and 6 attitude thrusters to control the 3-DOF attitude. The thrusters at present are primarily controlled by switching valves with constant value. Although the response bandwidth is high, the maneuverability is limited due to the constraint of finite thruster. The probability of interception will not be ensured if starting the guidance control in a short distance. Thus the interception strategy in accordance with the actual maneuverability should be designed.

3) Distance of Communication

Communication network should be established to ensure the wide field of view of MKV cluster that covers the whole targets group, so that effective assessment of the intercept process can be made. In addition, assuming CV is the manager of the system, KVs need the communication to receive commands from the commander. Restricted by technology, the communication distance between crafts is limited. So the formation of MKV group when approaching targets should keep the communication valid all the time.

4) Range of Detection

Interceptors are widely equipped with infrared detectors. The range of detection and field of view on carrier vehicle are always greater than those of KVs. So the CV should offer midcourse guidance commands to KVs in a short period of time. The range of detection of KV's detector determines the starting time of terminal guidance. According to the characteristics of detectors, a rational design of KVs' releasing time and the changing time from midcourse guidance to terminal guidance will increase the successful interception rate and control the energy consumption.

In summary, when the intercepting strategy and KVs' releasing time are decided, the constraints in the process should be fully taken into account to assign missions to KVs and make the planning of missions, and thus the design of intercepting strategy is finished.

3. INTERCEPTING PROCEDURE

The whole procedure of the interception is shown in Fig. 1. The interceptor missile is vertically launched from ground level with three-stage motor. Inertial guidance is used at first. When the targets are in sight of the detector, it comes to the midcourse phase that the missile is guided by the sensor on the main carrier vehicle. When the distance from the interceptor to the targets reaches a certain value, the KVs are released simultaneously. CV is the manager of all, so it scans the entire targets and does the threat analysis, and assigns every KV to intercept a different target. Then it comes to the terminal guidance phase that each vehicle is independently guided by its own detector.

Table 1. Parameters of the Infrared Seekers

Maximum detection range of CV	600 km
Maximum detection range of KV	400 km
Field of View of CV	3.5°
Field of View of KV	1°

While the target's warheads or decoys are detected by CV, the guidance course could be divided into two phases according to the parameters of the detectors and characteristics of targets. In this paper, according to US's SM-3 and GMD system, the parameters of the detectors are shown in table 1.

In the first phase, the whole cluster of targets can be detected by CV's detector, while the KVs' are out of reach. Assuming the average radius of the targets cluster is about $R_{tar} = 15km$. According to (1), the demarcation point is about $491km$ from the targets.

$$L = R_{tar}/tan(0.5\theta_{fov}) \tag{1}$$

After the demarcation point, CV's detector cannot get the whole cluster since the distance is too close. While targets come into the view of KVs' sensors, integrated guidance law is taken based on the fusion information from sensors and inertial guidance. In order to make the planning, CV uses the information transmitted from infrared seekers on

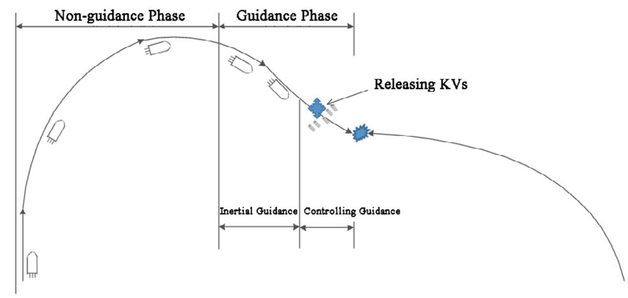

Fig. 1. Intercepting Procedure

KVs to merge an expansion view of the scene, so that the interception is always in charge of the CV.

4. MULTI-SENSORS FUSION METHOD

4.1 High-accuracy Position Measurement Method

1) Principle of Position Measurement Method

Limited by the payload's size, it is difficult for the interceptor to be equipped with a radar detector. Therefore, the infrared detector is used to make the guidance. However, infrared seeker can only track and measure angle information, and cannot output the actual position of the target. Hence, this article proposes a position measurement method based on multi-sensors fusion, so that accurate positioning information can be obtained by each KV.

The method is based on triangulation principle. Firstly, the inertial guidance system on KV is calibrated while KVs are released from CV. The distance between KV and CV is realtimely measured by the inertial guidance system. There will be a certain measurement error due to the zero drift of inertial guidance. Since the releasing time is no longer than dozens of seconds, the error will not be large enough to interfere with the measurement result. According to the direction measured by the infrared detectors and distance between KV and CV, the distance between KV and target could be solved.

2) Position Measurement

The position of the target can be measured by several infrared sensors together. Here we take two interceptors as an example. Assuming that the target is in the field of view of two interceptors simultaneously. The position of interceptors in the inertial reference frame S_i are $C_1(x_1, y_1, z_1)$ and $C_2(x_2, y_2, z_2)$ respectively. The attitude of interceptors are $(\phi_1, \theta_1, \psi_1)$ and $(\phi_2, \theta_2, \psi_2)$. The measurement data of the target by the infrared sensors are $P_1(m_1, n_1)$ and $P_2(m_2, n_2)$.

The principle of multiple sensors positioning method is shown in Fig. 2. The line of sight $\overrightarrow{C_1A}$ and the focal plane u_1v_1 intersect at $P_1(u_1, v_1)$. Assume that the distance between the focal point and interceptor's center of mass is ignored. The vector $\overrightarrow{C_1P_1}$ in body coordinate system of interceptor I S_{b_1} is:

$$(\overrightarrow{C_1P_1})_{b_1} = [f_1, m_1, n_1]^T \tag{2}$$

where f_1 is the focal length of the infrared sensor I.

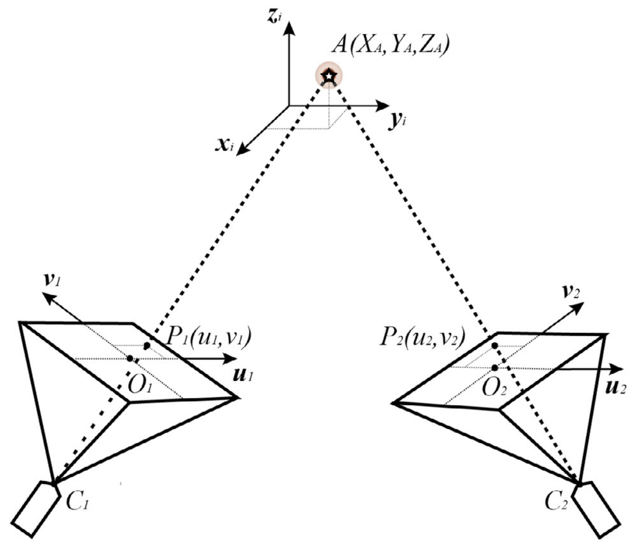

Fig. 2. Principle of Multi-Sensors Positioning Method

Transform the vector $\overrightarrow{C_1P_1}$ into the inertial reference frame:

$$(\overrightarrow{C_1P_1})_i = L_{ib_1} \cdot (\overrightarrow{C_1P_1})_{b_1} \tag{3}$$

where L_{ib} is the coordinate transformation matrix from S_b to S_i: ($C_\theta = cos\theta$, $S_\phi = sin\phi$, etc.)

$$L_{ib} = \begin{pmatrix} C_\theta C_\psi & -C_\phi S_\psi + S_\phi S_\theta C_\psi & S_\phi S_\psi + C_\phi S_\theta C_\psi \\ C_\theta S_\psi & C_\phi C_\psi + S_\phi S_\theta S_\psi & S_\phi - C_\psi + C_\phi S_\theta S_\psi \\ -S_\theta & S_\phi C_\theta & C_\phi C_\theta \end{pmatrix} \tag{4}$$

Similarly, vector $(\overrightarrow{C_2P_2})_i$ can be calculated.

Therefore, the problem has been changed into a geometric calculation. The point $C_1(x_1, y_1, z_1)$ is on line l_1, whose direction vector is $(\overrightarrow{C_1P_1})_i$. The point $C_2(x_2, y_2, z_2)$ is on line l_2, whose direction vector is $(\overrightarrow{C_2P_2})_i$. Solving the intersection point of line l_1 and l_2, the target's position can be obtained.

However, because of the existence of errors, P_1 and P_2 on the image cannot be precisely measured. Thus, line l_1 and l_2 may not intersect. On this occasion, the nearest point to the two lines can be used to substitute the intersection approximately, which is the midpoint of the common perpendicular segment. Sometimes it is not the best choice to use the midpoint, because the standard deviations of the KVs are greater than that of CV. To improve the confidence coefficient, we can choose a point closer to the CV's line of sight instead.

4.2 View Expansion of Multi-Sensors Method

Since the resolution of infrared detectors is limited, infrared lens with narrow field of view (FOV) is needed to improve the detection range, and thus to get relatively accurate spatial information of the target and adequate time to maneuver to hit the target. Currently, US GMD system uses the narrow FOV of 1°. However, it's pretty difficult for a single narrow FOV sensor to get the condition of the battle progress. Here we use all the sensors from KVs and CV to form up a expansion view, which is

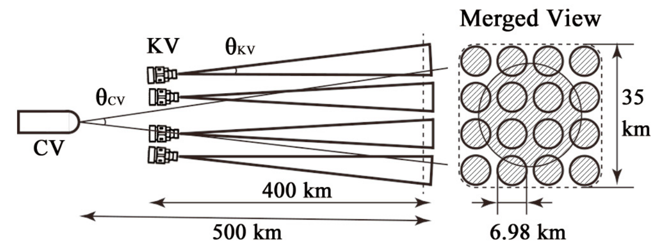

Fig. 3. Principle of Multi-Sensors View Expansion Method

able to cover the whole targets cluster. The merged image helps CV to make the planning and task allocation, which optimizes the intercepting guidance strategy. Moreover, using the overall expansion view can prevent problems such as repeated attack due to wrong dispensation order, and interference of trajectory. Hence, the method is of practical importance in midcourse interception.

The principle of view expansion method is shown in Fig. 3. When KVs are released from the carrier, their attitude are controlled firstly so that their formation shapes into a square matrix. In this paper, 16 KVs form up a 4×4 matrix. Assuming that the KVs are flying $100km$ ahead of the CV, $400km$ distance from the target cluster. According to (1), each KV's detector covers an area of $6.98km$ diameter, and the CV's detector covers an area of $30.55km$ diameter. Detecting information from each KV is transmitted back to the image processing unit on CV. Combined with the position and attitude of each detector, the processor can generate a merged view, as shown on the right of Fig. 3. The average diameter of the detecting area is improved to $35km$ approximately. At the center area of the image, several views are overlapping. Therefore, a more accurate image can be obtained with the help of proper fusion algorithms. The image quality at the edge of the merged view is comparatively low due to the exsistance of blind spot. Yet it can be corrected by the predictive algorithm, or simply ignored since the edge area is relatively empty.

5. TERMINAL GUIDANCE LAW OF KVS

During the terminal guidance phase, KVs are dispensed and guided to the targets by cooperative strategy. Since the size is small, KV is equipped with strapdown seeker at the head of it.

Proportional navigation is used by the KVs to make the interception. When approaching the target, the rotation rate of the interceptor's velocity vector $\dot{R}$ is proportional to the rotation rate of the line of sight $\mathbf{\Omega}$, and in the same direction.

According to the high-accuracy position measurement method mentioned in the previous paragraph, the target's position R_t can be worked out. Thus, the velocity vector V_t can be calculated by the finite difference R_t. Together with the position and velocity itself by inertial measurement unit, the relative position $\boldsymbol{R}_{mt}$ and relative velocity $\boldsymbol{V}_{mt}$ are:

$$\boldsymbol{R}_{mt} = x_r\boldsymbol{i} + y_r\boldsymbol{j} + z_r\boldsymbol{k} \tag{5}$$
$$\boldsymbol{V}_{mt} = V_{rx}\boldsymbol{i} + V_{ry}\boldsymbol{j} + V_{rz}\boldsymbol{k} \tag{6}$$

As to the derivative of $\boldsymbol{R}_{mt}$, we have:

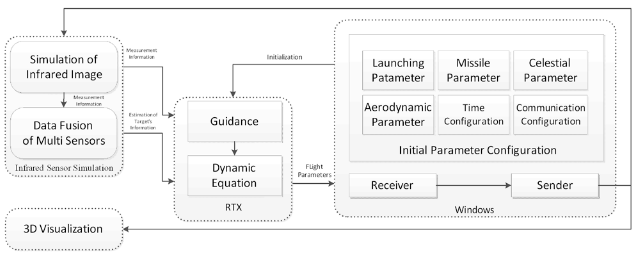

Fig. 4. System Architecture Diagram of MKV Cooperative Detection and Guidance Simulation System

$$\frac{d\boldsymbol{R}_{mt}}{dt} = \frac{\delta \boldsymbol{R}_{mt}}{dt} + \boldsymbol{\Omega} \times \boldsymbol{R}_{mt} \tag{7}$$

where $\boldsymbol{\Omega}$ is the is the rotation vector of the line of sight:

$$\begin{aligned} \boldsymbol{\Omega}_x &= \frac{y_r V_{rz} - z_r V_{ry}}{R^2} \\ \boldsymbol{\Omega}_y &= \frac{z_r V_{rx} - x_r V_{rz}}{R^2} \\ \boldsymbol{\Omega}_z &= \frac{x_r V_{ry} - y_r V_{rx}}{R^2} \end{aligned} \tag{8}$$

The rotation rate of the velocity vector $\dot{R}$ is:

$$\dot{R} = \frac{(x_r V_{rx} + y_r V_{ry} + z_r V_{rz})}{\sqrt{x_r^2 + y_r^2 + z_r^2}} \tag{9}$$

Transform $\boldsymbol{\Omega}$ to the wind frame:

$$\dot{\sigma}_{elv} = -\sin\theta \cdot \cos\psi_c \cdot \Omega_x + \cos\theta \cdot \Omega_y + \sin\theta \cdot \sin\psi_c \cdot \Omega_z \tag{10}$$

$$\dot{\sigma}_{az} = \sin\psi_c \cdot \Omega_x + \cos\psi_c \cdot \Omega_z \tag{11}$$

where $\dot{\sigma}_{elv}$ and $\dot{\sigma}_{az}$ denotes the y- and z-components of $\boldsymbol{\Omega}$ in the wind frame.

Use first order inertia element as the guidance signal filter model. The overload command is as following:

$$n_{elv} = \frac{K \left| \dot{R} \right| \dot{\sigma}_{az}}{(\tau s + 1) g} + g \cos\theta \tag{12}$$

$$n_{az} = \frac{-K \left| \dot{R} \right| \dot{\sigma}_{elv}}{(\tau s + 1) g} \tag{13}$$

where n_{elv} and n_{az} denotes the overload in y and z-axis. Variable K denotes the proportionality constant generally having an integer value 3-5, and τ_g denotes the time constant.

6. SIMULATION

In order to verify the correctness of the methods, a digital real-time simulation system is developed. The system consists of three modules including a dynamic calculation module, an infrared sensor simulation module, and a 3D visualization module, which is programmed in C++ language. The system architecture diagram is shown in Fig. 4.

The simulation parameter is shown in table 2.

Solving the kinetic equations of missiles by numerical method, the dynamic calculation module makes real-time simulation on the trajectory and attitude of the interceptors and targets, and generates guidance commands.

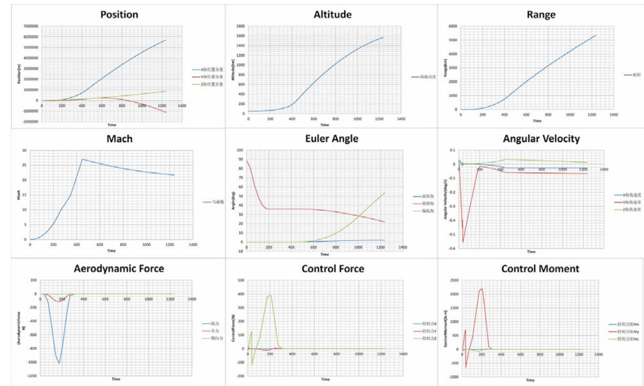

Fig. 5. Parametric Curves of Missile Simulation

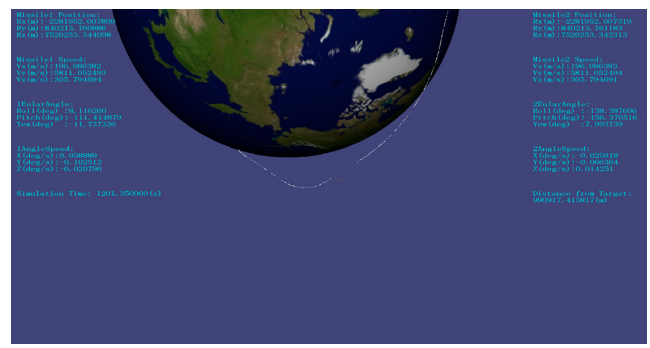

Fig. 6. Global View of the Intercepting Process

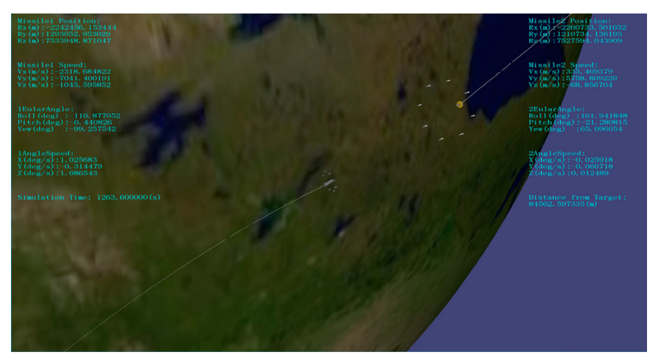

Fig. 7. Kill Vehicles Released Intercepting Multi-Targets

The simulating results are sent to the infrared sensor simulation module and 3D visualization module realtimely. By archiving the simulation data into parametric curves, the missile's state at any time can be clearly seen in the database. The parametric curves are shown in Fig. 5.

The 3D visualization module is programmed based on OpenSceneGraph (OSG) toolkit. Using the data collected from the calculation module, the system can demonstrate the whole dynamic process from launching till successfully intercepted based on Virtual Reality. The 3D simulation interface is shown in Fig. 6, and Fig. 7.

Table 2. Simulation Parameter

Stages of Rocket	3
Number of Kill Vehicles	16
Number of Targets' Warheads and Decoys	8
Altitude when Intercepting	1000 km
Maximum Velocity of Targets' Warheads	7700 m/s
Maximum Velocity of KVs	6500 m/s

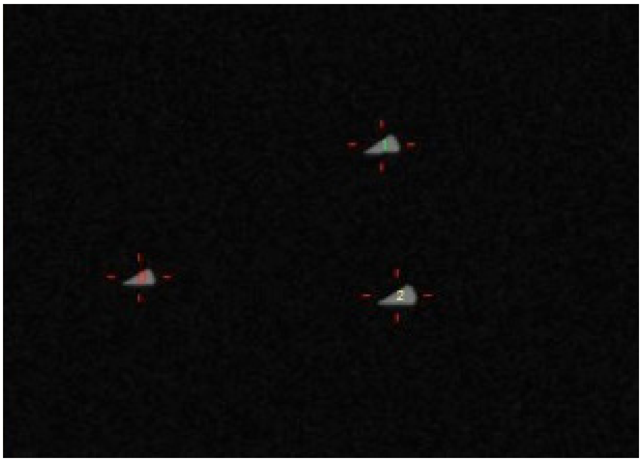

Fig. 8. Simulation of Infrared Seeker's View

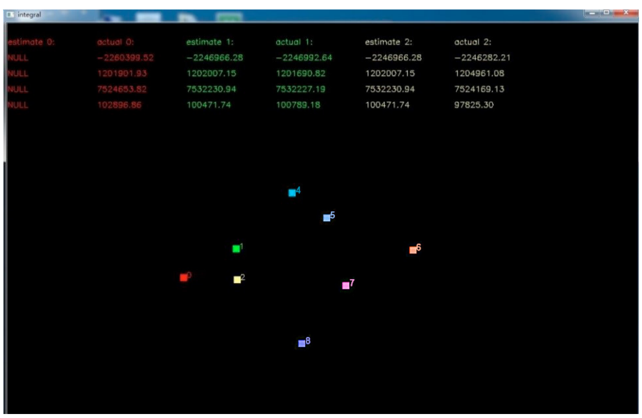

Fig. 9. Simulation of Multi-Sensors Fusion Method

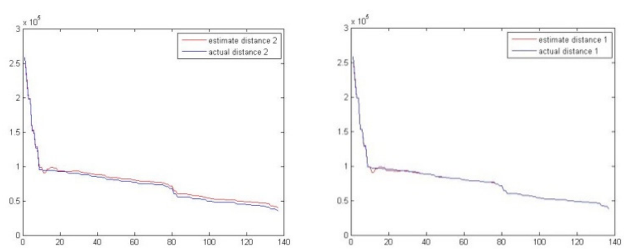

Fig. 10. Comparison between Actual Distance and Estimated Distance calculated by Fusion Method

The infrared sensor simulation module is programmed based on OpenGL graphics engine. The view of infrared seekers is simulated as in Fig. 8. The high-accuracy position measurement method and view expansion method are realized in the system, as shown in Fig. 9.

Compare the estimated position calculated by the fusion measurement method with the actual position of the target. It can be seen from Fig. 10 that the measurement result is in accordance with the actual value. The measurement result is sent back to the dynamic calculation module, which will then calculate the guidance law of KV. From the 3D visualization module, we can see that all the targets are precisely hit by KVs.

7. CONCLUSION

In this article, the intercepting strategy of MKV system during midcourse defense is analyzed. As to the infrared seekers on MKV, a position measurement method and a view expansion method during the intercepting process are proposed, and higher accuracy is accomplished. The terminal guidance law is analyzed based on the methods. A simulation system is developed. It proved the feasibility of the intercepting strategy and multi-sensors fusion methods, and verified the correctness of the terminal guidance algorithm.

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