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Recent interest in the use of guided kinetic energy missiles and projectiles for the air-defense and anti-missile application raises important questions on the suitability of current guidance mechanisms, and whether they will realize the minimum miss distance requirements of a hit-to-kill warhead. Traditional missile guidance algorithms require the use of a blast and fragmentation warhead and a proximity fuze to ensure target kill, since some miss distance is predictable, even with the use of a variable speed missile and sophisticated proportional navigation. A limited investigation into a more suitable hit-to-kill guidance approach was conducted, consistent with recent advances in computer and electronic miniaturization, which offer the possibility of alternate approaches to missile guidance. A first-order simulation demonstrates the usefulness of the proposed algorithm.

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DEVELOPMENT OF A HIT-TO-KILL GUIDANCE ALGORITHM FOR KINETIC ENERGY WEAPONS

SEPTEMBER 1988

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1. BACKGROUND

Recent interest in the use of guided kinetic energy missiles and projectiles for the air-defense and anti-missile application raises important questions on the suitability of current guidance mechanisms, and whether they will realize the minimum miss distance requirements of a hit-to-kill warhead. Traditional missile guidance algorithms require the use of a blast and fragmentation warhead to ensure target kill, since some miss distance is predictable. Currently, the use of sophisticated proportional navigation systems in conjunction with a variable speed missile may still result in an unreasonable missile turn rate and lateral acceleration at the end game, to ensure hit-to-kill against a maneuvering target. Therefore, a limited investigation into a more suitable hit-to-kill guidance algorithm was conducted, consistent with recent advances in computer and electronic miniaturization, which offer the possibility of alternate approaches to missile guidance.

2. KINEMATICS OF INTERCEPT COURSES

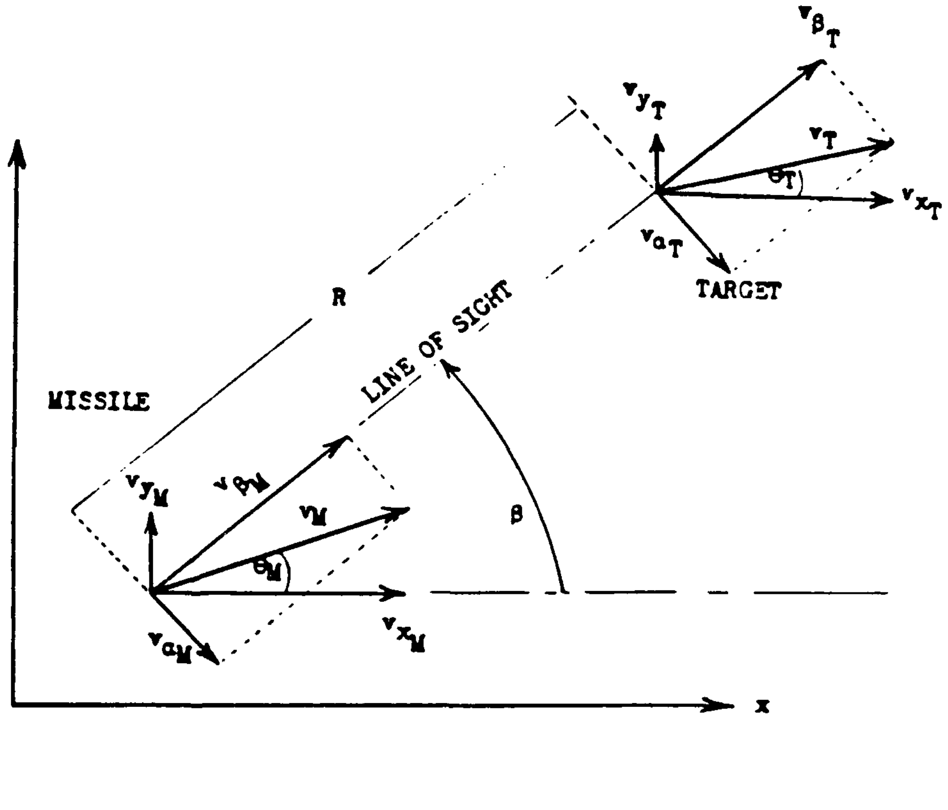
AMCP 706-107 provides a very concise and simplified explanation of the kinematics of different intercept algorithms which are typically employed by guided missiles.[1] That discussion is repeated here as an introduction to the guidance algorithm to be developed. Four of the five most common navigational methods for solving the intercept problem are shown in Figure 2.2. The fifth method, *deviated pursuit*, is a slight modification of the *pursuit* geometry, so it is not presented graphically, but will be discussed. Before any of these methods can be analyzed, the geometry of the intercept problem is defined in Figure 2.1.

Figure 2.1
Geometry of the Intercept Problem

θ is angle of heading
β is angle of line of sight
R is range between missile and target
υ is velocity vector
γ is missile to target velocity ratio,

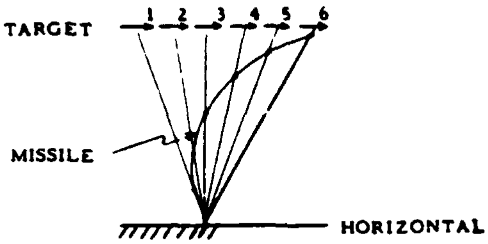
$$\left(\gamma = \frac{\upsilon_M}{\upsilon_T}\right)$$

subscript M refers to missile
subscript T refers to target
subscript β refers to direction along the line of sight
subscript α refers to direction perpendicular to line of sight

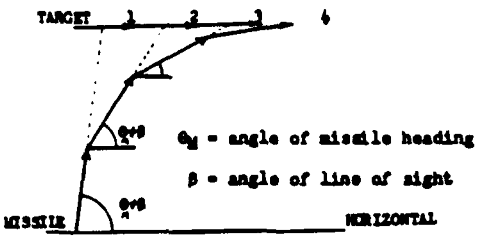


1 *Research and Development of Materiel, Engineering Design Handbook: Elements of Armament Engineering Part Two, Ballistics.* AMCP 706-107, Army Materiel Command, September 1963.

Figure 2.2
Kinematics of Intercept Courses

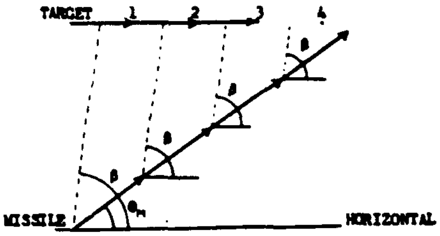


(a) Line of sight. Defined as a course in which the missile is guided so as to remain on the line joining the target and point of control.



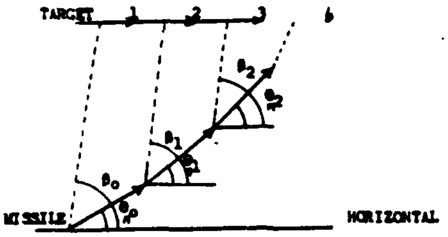
(b) Pursuit. Lead or deviated pursuit course is defined as a course in which the angle between the velocity vector and line of sight from the missile to the target is fixed. For purposes of illustration, lead angle is assumed to be zero and only pure pursuit is described

$(\theta_M = \beta)$.



(c) Constant bearing. A course in which the line of sight from the missile to the target maintains a constant direction in space. If both missile and target speeds are constant, a collision course results

$\left(\frac{d\theta}{dt} = \dot{\beta} = 0\right)$.



(d) Proportional. A course in which the rate of change of missile heading is directly proportional to the rate of rotation of the line of sight from the missile to target

$\left(\frac{d\theta_M}{dt} = K\frac{d\beta}{dt} \text{ or } \dot{\theta}_M = K\dot{\beta}\right)$.

Using the geometry in Figure 2.1, several relationships between the parameters are presented.

The range R, at any given time:

$$R=\int_0^t\left(v_{\beta_T}-v_{\beta_M}\right)dt+R_{initial} \tag{1}$$

Intercept will take place only if R is always decreasing and for R to decrease

$v_{\beta_T}-v_{\beta_M}<0$, or negative.

The rate of change of the range is:

$$\begin{aligned}\frac{dR}{dt}&=\dot{R}=v_{\beta_T}-v_{\beta_M}\\ &=v_T\cos(\theta_T-\beta)-v_M\cos(\theta_M-\beta)\\ &=v_M\left[\frac{1}{\gamma}\cos(\theta_T-\beta)-\cos(\theta_M-\beta)\right]\end{aligned} \tag{2}$$

and

$$\begin{aligned}\frac{d\beta}{dt}&=\dot{\beta}=-\frac{v_{\alpha_T}-v_{\alpha_M}}{R}\\ &=-\frac{v_T\sin(\theta_T-\beta)-v_M\sin(\theta_M-\beta)}{R}\\ &=-\frac{v_M\left[\frac{1}{\gamma}\sin(\theta_T-\beta)-\sin(\theta_M-\beta)\right]}{R}\end{aligned} \tag{3}$$

Based on these mathematical relationships, the following characteristics of the navigational methods follow.

A. Line of Sight (Beam Rider)

A beam rider always flies the line of sight from a tracker on the ground to the target and requires associated ground equipment to illuminate the target and provide the missile with path deviation signals. Turning rates are always finite when $\gamma > 1$, hence, lateral accelerations must be determined as functions of altitude, range, relative missile velocity, and angle of the line of sight, β.

B. Pure Pursuit

The missile is always headed toward the target along the line of sight:

$$\theta_M = \beta$$

$$\upsilon_{\beta_M} = \upsilon_M \cdot \theta_M = \beta \rightarrow \theta_T$$

In other words, intercept takes place from the tail of the target, unless the target is met head on. The missile must maneuver but the pursuit course is the simplest to mechanize in a guidance system. With pure pursuit navigation, the lateral acceleration of a missile attacking a non-maneuvering target will be infinite at the instant of intercept if the missile velocity is more than twice the target velocity. The lateral acceleration will be zero at the instant of intercept if the missile velocity is less than twice the target velocity. From these observations, unless some miss distance is allowable, it is impractical to use a pursuit course when the missile velocity exceeds twice the target velocity, since it will be impossible to achieve an infinite lateral acceleration.

C. Deviated Pursuit

A deviated pursuit course is where the angle between the missile velocity vector V_M and the line of sight $(\theta_M - \beta)$ is fixed. Thus, if $\delta = \beta - \theta_M$, **(2)** and **(3)** become, respectively:

$$\dot{R} = V_T \cos\beta - V_M \cos\delta \qquad (4)$$

$$\dot{\beta} = -\frac{V_T \sin\beta - V_M \sin\delta}{R} \qquad (5)$$

Figure 2.3 shows a plot of the relationship between γ and $\sin\delta$ which must exist in order that $\dot{\beta}$ remain finite (Region II) or zero for the deviated pursuit.

One sees that only for $1 = \gamma \leq 2$ will it be possible to select a δ which does not yield an infinite turning rate. Of course, in practice, when turning rates called for are in excess of the maximum missile turning rate, the missile will remain in its maximum turn until it cuts across the line of the target path and then re-enters the proper course or is lost. Since lateral acceleration, $a_M = V_M\dot{\beta}$, characteristics of turning rate apply to lateral accelerations when V_M is constant.

D. Constant Bearing

The missile is navigated so that the target always has the same bearing, $\dot{\beta} = 0$. For a non-maneuvering target moving with a constant velocity, this means that a missile with constant velocity will ideally be directed onto a straight line collision course. In practice, however, inherent system errors and dynamic lag has historically made a perfect constant bearing course difficult to achieve. This technique is most often used for the anti-aircraft artillery fire control problem, where the computer determines θ_M , the direction to point the guns in order to accomplish intercept.

E. Proportional

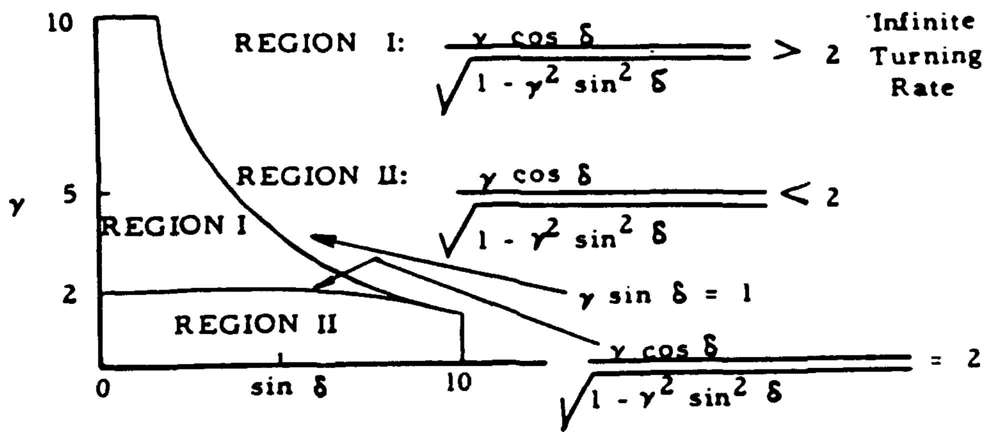
The angular velocity $\dot{\theta}_M$, of the missile is a constant K, times the angular velocity, $\dot{\beta}$ of the line of sight; $\dot{\theta}_M = K\dot{\beta}$. Hence, $\theta_M = K\beta + \theta_0$. Both pursuit and constant bearing navigation methods are special cases of proportional navigation. For example:

When $K = 1$ and $\theta_0 = 0$, $\theta_M = \beta$, which is pursuit navigation.

When $K = \infty$, then $\dot{\beta} = \frac{\dot{\theta}_M}{\infty} = 0$, which is constant bearing navigation.

It could be shown that for a maneuvering target and a variable speed missile, the required missile rate of turn, $\dot{\theta}_M$, is always finite when $K \geq 4$. Most operational guided missile weapons are designed with some type of proportional navigation.

Figure 2.3
Conditions for Finite Turning Rate (Deviated Pursuit)



3. THE HIT-TO-KILL GUIDANCE CHALLENGE

The above guidance methods, which have found wide spread use in the guided missile as well as anti-aircraft fire control application each present unique challenges to the kinetic energy hit-to-kill weapon system. The line of sight and pursuit modes start the guided projectile upon a course aimed directly at the target, which clearly will not be there when the projectile arrives. These techniques knowingly waste much needed kinetic energy bringing the projectile on to the target, even if the target is non-maneuvering. In a kinetic energy type missile or projectile application, the projectile is expected to be traveling at velocities in excess of those typically found in modern guided missiles. At such high rates of travel, even small turning rates will create large transverse loads on the projectile structure. In addition, the heat management and structural effects of high speed travel on aerodynamic control surfaces will be significant. If thrust vectoring or thrust attitude control is employed on the kinetic energy projectile or missile, efficient use of these control resources will be required to ensure that overall parasitic weight is minimized. For these reasons, it makes little sense to intentionally aim the missile to miss the target in the early stages of the intercept.

Proportional navigation begins to employ a more energy efficient target intercept algorithm. As Figure 2.1 (d) shows, by initially leading the target, a high speed missile will anticipate where the target will eventually be and will gradually change direction and be brought onto a collision course which is more perpendicular to the flight path of the target. The rate at which the missile will deviate its course is a function of the navigation constant K and the crossing speed of the target. A faster target will force a faster turning rate in the missile for the same value of K. A higher or lower value of K will bring the missile onto the target faster or slower, respectively for the same target speed. Clearly, the value of K designed into the missile must be an acceptable average based on the performance parameters of various targets to be engaged. As mentioned earlier, a value of $K \geq 4$ ensures that the missile turn rate is always finite. However, this finite rate may also be unreasonably high for a kinetic energy projectile or missile. In addition, the maximum turning rate of the missile will occur just before intercept, when the missile is at its most perpendicular aspect to the target. Therefore, a highly agile target may still be able to shake off the kinetic energy projectile at the last instant, since the missile navigation constant K has a multiplying effect on the required missile maneuvering acceleration.

4. THE OPTIMUM HIT-TO-KILL INTERCEPT ALGORITHM

Thus far, this discussion has identified the intercept limiting parameters of turning rate, lateral acceleration, and for the kinetic energy projectile or missile, its intercept energy efficiency. As a result, the one intercept concept which minimizes turning rate, lateral acceleration, while at the same time ensuring efficient use of the missile maneuver energy, is one which involves a constant bearing. Although it was pointed out that in the past a constant bearing intercept required a cooperative target in the sense that it did not maneuver after projectile launch, which is why it is employed with air-defense guns, the following analysis will show that even if the target is highly agile, continuously updating the constant bearing direction remains the most efficient intercept approach for a high speed and guided kinetic energy hit-to-kill missile or projectile. This approach also remains the most efficient if the target is non-maneuvering or following a predictable ballistic trajectory.

Figure 4.1 shows the three-dimensional geometry used to develop this hit-to-kill algorithm. From the nomenclature shown in Figure 4.1, the approach to the intercept solution is to define the missile and target in terms of their position and velocity vectors. The vector components for the missile and target position and velocity may be defined based on any arbitrary inertial reference frame. The most convenient may simply be the instantaneous location of the missile, since this will result in the x_M, y_M, and z_M terms reducing to zero. Then solve the system of simultaneous equations to identify the intercept point for that moment in time.

Once this intercept point is identified, the missile turn angle, Θ, required to place the missile onto the intercept vector is calculated. The missile then executes its maximum turning rate on to this intercept vector, by turning through the angle Θ. During flight, the target and missile position and velocity vectors are updated and additional course corrects are made accordingly. The following equations develop the mathematics for this algorithm.

$$|\bar{V}_T| = \sqrt{a_T^2 + b_T^2 + c_T^2} = V_T \quad (6)$$

$$|\bar{V}_M| = \sqrt{a_M^2 + b_M^2 + c_M^2} = V_M \quad (7)$$

$$\bar{V}_M = a_M\hat{i} + b_M\hat{j} + c_M\hat{k} \quad (8)$$

$$\bar{V}_T = a_T\hat{i} + b_T\hat{j} + c_T\hat{k} \quad (9)$$

$$\bar{R}_{MI} = (x_I - x_M)\hat{i} + (y_I - y_M)\hat{j} + (z_I - z_M)\hat{k} \quad (10)$$

$$\bar{R}_{TI} = (x_I - x_T)\hat{i} + (y_I - y_T)\hat{j} + (z_I - z_T)\hat{k} \quad (11)$$

$$|\bar{R}_{MI}| = V_M\Delta t \qquad \text{where,} \quad \Delta t = \text{time to intercept} \quad (12)$$

$$|\bar{R}_{TI}| = V_T\Delta t \quad (13)$$

The missile guidance system then must continuously solve the following system of four simultaneous equations in order to get the intercept point in three dimensions:

$$x_I - x_T = a_T\Delta t \quad (14)$$

$$y_I - y_T = b_T\Delta t \quad (15)$$

$$z_I - z_T = c_T\Delta t \quad (16)$$

$$V_M\Delta t = \sqrt{(x_I - x_M)^2 + (y_I - y_M)^2 + (z_I - z_M)^2} \quad (17)$$

The intercept point is most easily calculated once the intercept time Δt is solved. Δt can be solved with the following quadratic equation based on the missile and target vectors:

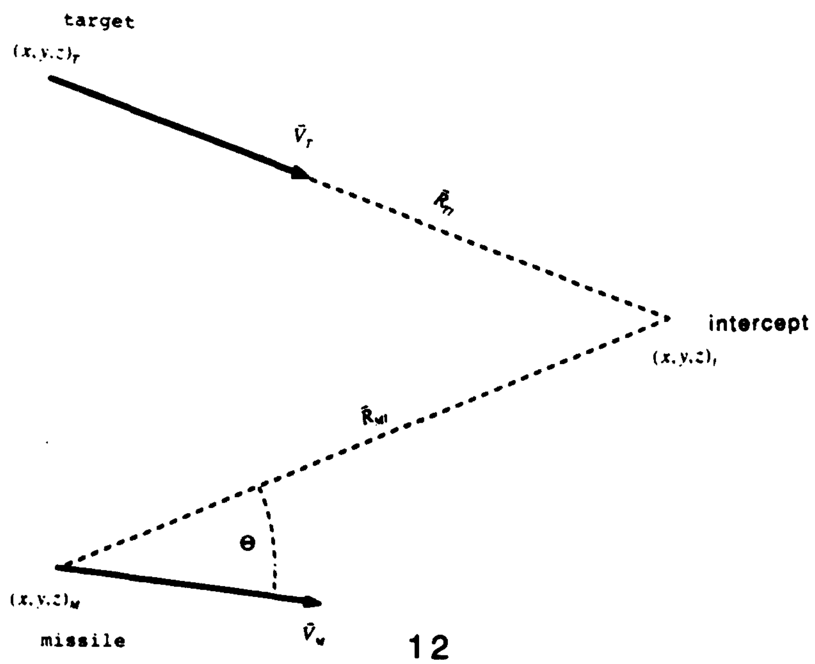
$$\Delta t = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{18}$$

where,

$$A = \left[a_T{}^2 + b_T{}^2 + c_T{}^2 - V_M{}^2\right]\Delta t^2$$
$$B = \left[2a_T(x_T - x_M) + 2b_T(y_T - y_M) + 2c_T(z_T - z_M)\right]\Delta t$$
$$C = \left[(x_T - x_M)^2 + (y_T - y_M)^2 + (z_T - z_M)^2\right]$$

Select only the positive value for Δt . At this point x_I, y_I, and z_I, fall out of equations **(14)**, **(15)**, and **(16)**. The angle, Θ, and its orientation with respect to the inertial reference frame is determined by resolving the dot and cross products of the missile velocity and intercept range vectors, previously calculated.

Figure 4.1
Three-Dimensional Hit-to-Kill Intercept Geometry



5. HIT-TO-KILL SPEED AND TURNING RATE REQUIREMENTS

Employing the above hit-to-kill intercept algorithm results in the following missile speed and turning rate requirements to ensure a hit on any maneuvering target.

A. Hit-to-Kill Missile Speed Requirements

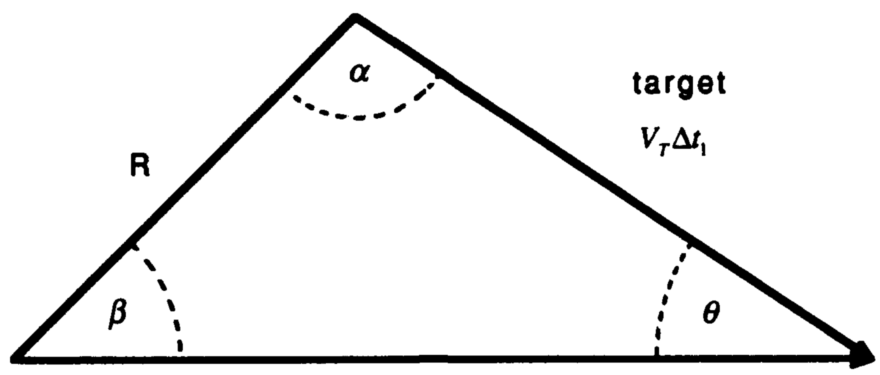
Figure 5.1 shows the general two-dimensional triangular relationship between the missile (subscript *M*), the target (subscript *T*), and their closing range (*R*) vectors, once the missile is oriented onto the appropriate instantaneous intercept vector. The two-dimensional representation is valid for this analysis, since the most efficient intercept will be realized once the missile has oriented itself into the two-dimensional plane with the target velocity vector. This maneuver of converting the intercept to a two-dimensional problem should be the first performed by the intercepting missile. Based on the triangular intercept geometry, the following observations can be made on the required missile to target speed, depending on the resulting direction of intercept:

for $\frac{V_M}{V_T} \le 1, \quad \beta \le \frac{\pi}{2}$

for $\frac{V_M}{V_T} > 1, \quad 0 \le \beta \le \pi$

In other words, in order to ensure that the missile can intercept all possible targets, from all attack directions, the missile must be able to fly, at a minimum, slightly faster than the target. With this relationship, the time of flight becomes the only variable. Nevertheless, an intercept is always possible if the missile flies faster than the target. Naturally, other operational requirements, in addition to the need for high impact velocity to realize a kinetic energy kill, will dictate a much higher missile to target velocity ratio. However, from a theoretical standpoint, extremely high rate of missile travel is not required for intercept.

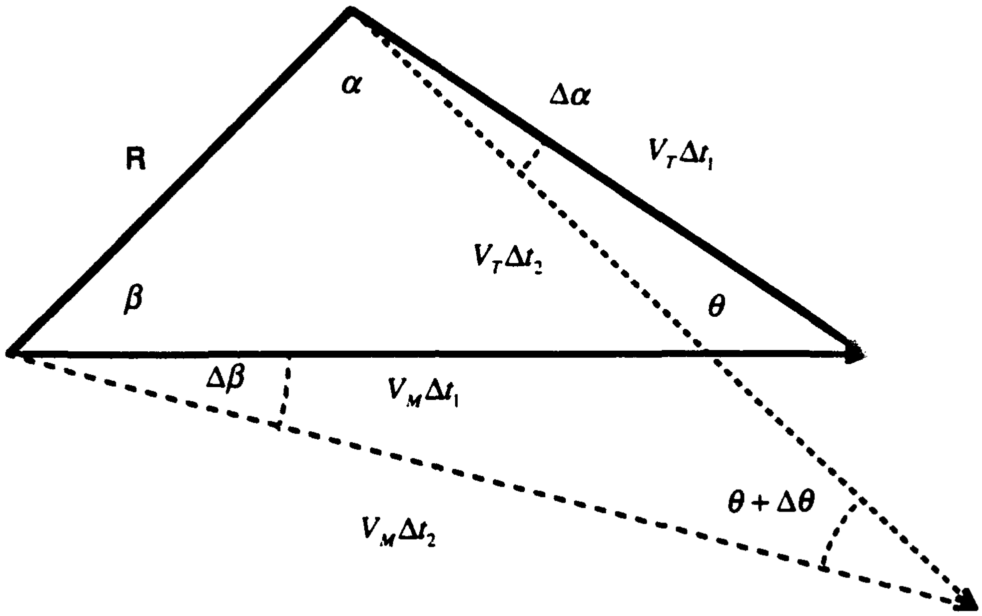
Figure 5.1
Two-Dimensional Hit-To-Kill Intercept Geometry



B. HIT-TO-KILL MISSILE TURNING RATE REQUIREMENTS

For all practical purposes, the target is expected to attempt evasive action in order to avoid being hit. In addition, the effect of target evasive action on the required missile turning rate and resulting lateral acceleration must also be understood. Figure 5.1 showed the two-dimensional triangular relationship between the missile and target vectors and the closing range vector, once the missile was oriented on the most efficient instantaneous intercept angle. In Figure 5.2, the target attempts an evasive maneuver by turning through the angle $\Delta\alpha$, which sets up an intercept angular error, $\Delta\beta$. The following equations formulate the required missile turning rate, $\dot{\beta}$, and the centripetal acceleration in order to bring the missile onto the next instantaneous intercept vector.

Figure 5.2
Geometry of an Evasive Maneuver



base on the geometry in Figure 5.2:

$$V_M\Delta t = \frac{V_T\Delta t\sin(\alpha)}{\sin(\beta)} \tag{19}$$

defining $\frac{1}{\gamma}=\frac{V_T}{V_M}$

yields

$$\sin(\beta)=\frac{\sin(\alpha)}{\gamma} \tag{20}$$

differentiating **(20)** with respect to time:

$$\dot{\beta}=\frac{\cos(\alpha)}{\gamma\cos(\beta)}\dot{\alpha} \tag{21}$$

What would be interesting to know is under what conditions does a target maneuver result in a maximum required missile maneuver, in order to remain on an appropriate intercept path. In other words, based on the velocity and angular relationship defined in **(21)**, when does a change in α maximize a change in β, and by how much? To answer this, equation **(20)** is differentiated twice with respect to α, and then evaluated for the angular conditions which maximize the rates of change.

differentiating **(20)** with respect to α yields:

$$\cos(\beta)\frac{d\beta}{d\alpha}=\frac{\cos(\alpha)}{\gamma} \tag{22}$$

and the second derivative becomes:

$$\frac{d^2\beta}{d\alpha^2}=\frac{-\sin\beta\left(1-\frac{\left(\frac{1}{\gamma^2}-\sin^2(\beta)\right)}{\cos^2(\beta)}\right)}{\cos(\beta)} \tag{23}$$

evaluating **(23)** for the maximum condition:

$$\frac{d^2\beta}{d\alpha^2}=0$$

when

$$\beta=0$$

and

$$\left(1-\frac{\left(\frac{1}{\gamma^2}-\sin^2(\beta)\right)}{\cos^2(\beta)}\right)=0$$

when

$$\frac{1}{\gamma}=1$$

or

$$V_M=V_T$$

which occurs under the following angle conditions:

$\beta = 0, \pi$

$\alpha = 0, \pi$

In other words, when the missile and target are flying parallel to each other, in either a head-on closing or tail-chase condition, any turn performed by the target maximizes the required turn by the missile, in order to affect an intercept.

Evaluating **(21)** for the maximum turning rates yields:

$$\dot{\beta}_{\max(missile)} = \frac{1}{\gamma} \frac{\cos(0, \pi)}{\cos(0, \pi)} \dot{\alpha}_{\max(target)}$$

or

$$\dot{\beta}_{\max(missile)} = \frac{V_M}{V_T} \dot{\alpha}_{\max(target)} \qquad \textbf{(24)}$$

In summary, equation **(24)** shows that the missile will be required to turn through an angle in proportion to the target's evasive turn, which is multiplied by the ratio of the missile to target speeds. However, in spite of the greater turning rate requirement, this is easily accomplished by the missile, since it is flying faster and will sweep out the required angle proportionally faster. In addition, since the missile intends to fly to where the target will again be located, the lateral acceleration requirement when performing this heading correction turn is not magnified by the ratio of missile to target speeds, as shown:

From the geometry in Figure 5.2, the angular rates can be defined by:

$\dot{\beta} = \omega_T$

$\dot{\alpha} = \omega_M$

Circular motion defines the following acceleration relationships for both the missile and the target, based on their turning rates:

$$\omega_{T_{max}} = \frac{gA_{T_{max}}}{V_T} \qquad \omega_{M_{max}} = \frac{gA_{M_{max}}}{V_M} \tag{25}$$

where A is the normal or centripetal acceleration due to circular motion.

Using **(24)** and equating the missile acceleration to the target acceleration by substituting equation **(25)** yields:

$$\frac{gA_{T_{max}}}{V_T} = \frac{V_M}{V_T}\frac{gA_{M_{max}}}{V_M} \tag{26}$$

and equation **(26)** reduces to:

$$A_{T_{max}} = A_{M_{max}} \tag{27}$$

Therefore, even under the most extreme evasive action conditions, with this hit-to-kill algorithm, the missile will only have to perform a turn which induces a lateral acceleration no greater than the lateral acceleration with which the target is making its evasive turn. There is no lateral acceleration magnification due to a greater missile to target speed ratio.

6. EXAMPLE INTERCEPTS

To give perspective to the kinematics of this hit-to-kill algorithm, the equations were modeled in a simple computer simulation. The following figures show the missile response, depending on the velocity ratio and the target evasive action. For each of these example intercepts, the target is simply performing a maximum acceleration turn, which places it in a circular path. The target parameters are a flight speed of 500 meters/sec, or approximately Mach 1.5, and its maximum lateral acceleration is 9 Gs. This acceleration limit corresponds to the performance limitation of typical fighter aircraft, based on the endurance of the pilot. At this speed and acceleration, the target will be making a turn with a radius of approximately 2800 meters. For all intercepts, the missile will be similarly limited in its lateral acceleration to 9 Gs. Although, without a pilot, the missile could easily perform at a higher acceleration level, since air frames can usually be designed considerably stronger. Nevertheless, this acceleration limitation tests the minimum requirements for intercept.

Figure 6.1 shows the resulting intercept when the kinetic energy missile is fired directly at the target, at a range of 20 km, at a flight speed of 2000 meters/second or about Mach 6. Intercept occurs within 12 seconds. Despite the target's great agility, the missile anticipates where it will eventually be, even though this point is continuously changing, and makes a direct hit with minimum course correction. Figure 6.2 shows an intercept with a 1000 meter/sec or Mach 3 missile (intercept in 25 seconds), and Figure 6.3 shows the intercept when the missile flies at only 700 meters/sec or Mach 2 (intercept in 32 seconds). Although in the last two intercepts, the target turns completely around and heads back at the missile, the intercept is doubly stressed, since the target twice passed through the maximum turn rate requirement. Had the target straightened out or changed turn direction, the missile would still have found it, since even the target must make a smooth transition when changing direction. As with any type of target maneuver, the next instantaneous intercept point is readily predicted.

Figure 6.1
Example Intercept
(V_m 2000 m/s, V_t 500 m/s, R_0 20 km)

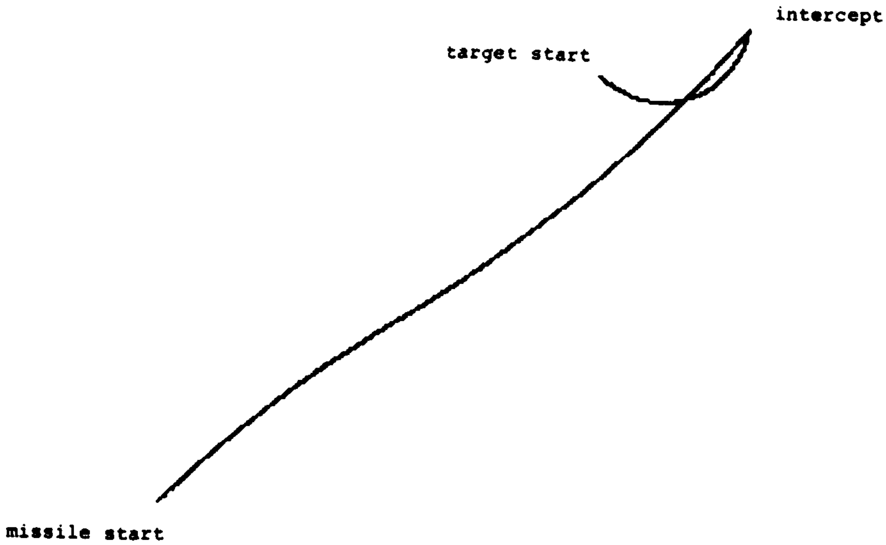


Figure 6.2
Example Intercept
(V_m 1000 m/s, V_t 500 m/s, R_0 20 km)

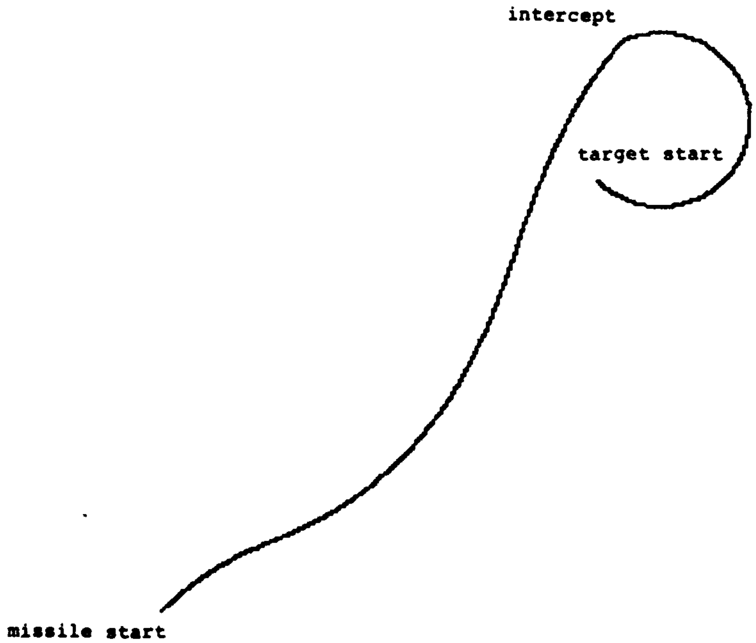
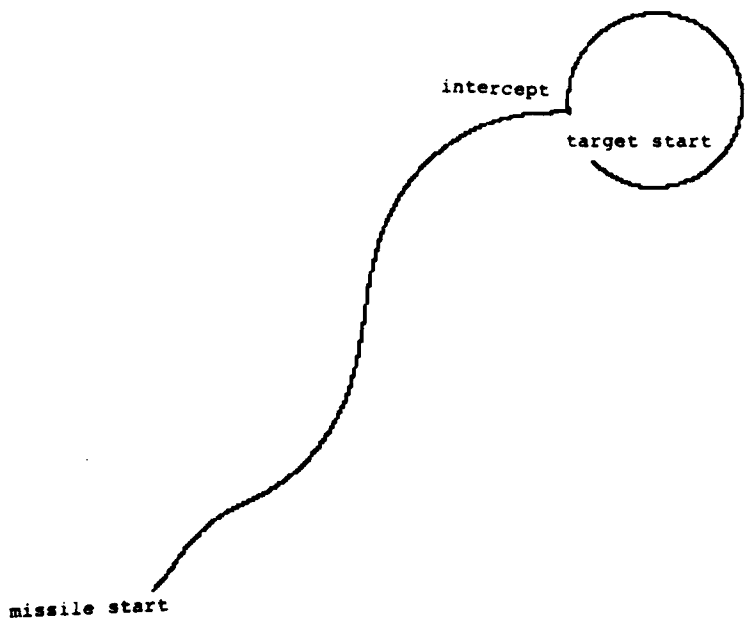


Figure 6.3
Example Intercept
(V_m 700 m/s, V_t 500 m/s, R_0 20 km)



7. SUMMARY AND CONCLUSIONS

This analysis has shown that a suitable hit-to-kill algorithm exists which is compatible with the high velocity guidance challenges of kinetic energy warhead projectiles and missiles. The kinematics of this algorithm also show that the interceptor is required, at a minimum, to be able to fly at least faster than the target to ensure an intercept solution from all possible engagement directions, endurance and KE kill limitations not withstanding. More significant is the observation that using this guidance algorithm greatly reduces the lateral acceleration requirements of the interceptor. To ensure an intercept against a maneuvering target, this algorithm requires that the missile simply be able to withstand at least as much lateral acceleration as the target. When considering the set of realistic targets to include manned aircraft, cruise missiles, and tactical ballistic missiles, achieving this level of structural and maneuver performance in an interceptor is well within the state-of-the-art. Development of suitable guidance, control, and sensor/tracker hardware, in particular to satisfy the need for accurate position and velocity vector determination for both the missile and target, remains to be demonstrated. However, advances in computer miniaturization and large increases in processing speed, coupled with miniature inertial sensors, with or without the use of global positioning sensors remove much of the difficulty in implementing this algorithm. The clear advantages to the use of this guidance approach make investigation of the hardware requirements compelling.