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London WC1A 2RA(GB)(54) **Early warning tracking system.**

(57) An early warning tracking system wherein a predefined polygonal zone's position is compared with an uncertainty region projected out in front of each approaching object. Conflicts of the uncertainty regions with the predefined polygonal zone are first considered in two dimensions and finally, in a third dimension only if a lateral intrusion is preliminarily indicated. The uncertainty regions as defined are a function of the position and velocity determination as well as the variances and covariance associated with the positional and velocity determinations.

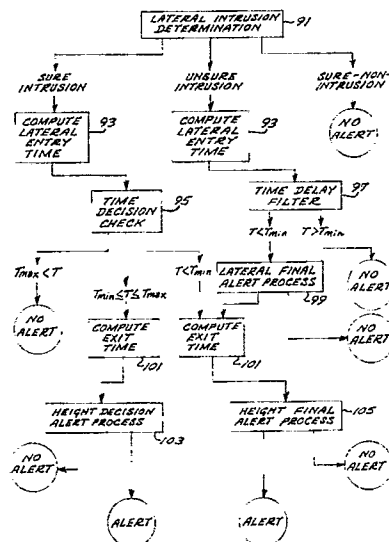


FIG. 2

EARLY WARNING TRACKING SYSTEM

BACKGROUND OF THE INVENTION5 Field of the Invention

This invention relates generally to computerized methods to provide early warning of collision for a tracking system and pertains more particularly to a process for predicting the probability that an object being tracked will intrude into a predefined polygonal zone.

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Description of the Related Art

A variety of computerized systems have been developed that are capable of predicting if and when an approaching object will intrude into a predefined region of space. Such systems are typically employed to protect secure zones, such as, for example military installations, to enable appropriate counter measures to be invoked on a timely basis. In addition, these systems are employed in air traffic control systems to assist air traffic controllers in discerning which amongst a potentially large number of objects being tracked are likely to present the possibility of a collision with the ground, restricted airspace or off designated air routes.

Performance of previous systems, especially those with relatively simple tracking and collision prediction algorithms, often is limited in that in order to solve the probabilities presented by modern vehicle performance envelopes and a relatively large number of closely spaced vehicles being tracked, large amounts of calculations are performed for too many of the objects being tracked. Since the data processing resources available are generally limited, this naturally serves to limit the number of objects such systems can process and increases the probability that false alarms of intrusion or collision will increase, especially when the objects are moving at high speeds, or are capable of rapid and unpredicted changes in path. All of these limitations are exacerbated by uncertainties in the position or velocities of the vehicle being tracked.

A significant aspect of the shortcomings of some prior art systems is the manner in which the uncertainty of positional determinations and velocity vector determinations are accommodated in the calculations. Typically, buffer zones are placed both inside and outside the predefined polygonal region to be protected to take into consideration the probable extent of potential tracking errors. If a tracked object is predicted to pierce the inside zone, then a sure lateral intrusion is declared. If, on the other hand, a tracked object is predicted not to pierce the outside zone, then a sure non-intrusion is declared. An unsure intrusion is declared if the object is predicted to penetrate somewhere between the peripheries of the inside and outside buffer zones. The problem with this method is determining the actual boundaries of the buffer zones. An accurate construction of the zones based on track variances has proved intractable. Not only do such systems have trouble accommodating large numbers of objects, especially ones moving at high velocities, but often false alarms and undetected intrusions result.

Therefore, there remains a need for a method of calculating the probability that a large number of objects being tracked will neither collide with one another or intrude on a predefined area within the tracking region. Furthermore, it would be highly beneficial if such a system were economical in its data processing requirement and was adaptable to a wide variety of accessories.

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SUMMARY OF THE INVENTION

The general purpose of the invention is to provide an early warning tracking system that is quickly able to discern whether an approaching object will intrude into a predefined polygonal zone. To attain this goal, the present invention first projects an uncertainty region in the instantaneous direction of travel of each approaching object and then makes decisions regarding the potential for intrusion, depending on the location of the predefined polygonal zone and its relationship to the location of the uncertainty region. To further simplify all subsequent calculations, the coordinate system is reoriented along the velocity vector for each approaching object. The new coordinates of the periphery of the predefined polygonal zone resulting from the reorientation are then considered with respect to the uncertainty region of each approaching

object. The limits of the uncertainty regions are determined by the variances associated with the positional and dynamic determinations of the objects being tracked.

The potential for intrusion is first considered in two dimensions to simplify processing. If no lateral intrusion is indicated, no further consideration is given to that particular object. Only after a possible lateral intrusion is indicated, is the object's perceived height and rate of change of height considered to further determine whether an intrusion into the predefined polygonal zone is probable.

The association of a unique uncertainty region with each approaching object, as opposed to the redefinition of buffer zones about the polygonal zone for each approaching object, greatly simplifies the required calculations and thereby enables the system of the present invention to more quickly and reliably yield information regarding the potential for intrusion into the predefined polygonal zone.

Other features and advantages of the present invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, which illustrate by way of example, the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic representation of a scenario for which employment of the present invention is well suited;

Figure 2 is a flow chart illustrating the order and organization by which the various determinations and calculations of the present invention are performed;

Figure 3 is a flow chart illustrating in more detail the method of determination 91 illustrated in Figure 2;

Figure 4 illustrates the reorientation of the coordinate system by the system of the present invention;

Figure 5 illustrates all possible orientations of predefined polygonal zones relative to an approaching object's uncertainty zone.

Detailed Description

Fig. 1 generally illustrates the situation and conditions for which the deployment of the system and methods of the present invention are intended. Schematically illustrated in a top plan view is the airspace in and around a predefined polygonal region 61 (having vertices 69-74) in which a multitude of objects are moving at different speeds and directions. Each such object's position is depicted by a dot 63 while its velocity vector, depicted by an arrow 65, is an indication of the speed and direction of its trajectory. It is the function of the present invention to predict which of the multitude of objects presents a high likelihood of intruding into region 61 at a predefined critical time. This system and its methods can for example assist air traffic controllers in monitoring and controlling the air space in and around a busy airport by directing attention to only those aircraft that are on direct approach, or, help prioritize the deployment of countermeasures for the protection of a restricted military zone.

Figure 2 illustrates the overall flow of decisions and logic employed to issue a timely alert regarding an impending intrusion. Upon detection of the presence of an object by an associated tracking system, the system of the present invention first makes a determination 91 whether the object is sure to intrude laterally, will surely not intrude laterally, or might intrude laterally. This determination is based on the object's perceived position and track velocity as projected onto a horizontal plane presumes that it will not deviate from its flight path and also takes into consideration the uncertainty inherent in the tracking measurements. At this point only the lateral intrusion into the predefined region is of concern and therefore, position and movement are considered only in two dimensions as depicted in Figure 1.

The chronology of decisions that are made and computations that are performed to provide this first determination 91 are set forth in more detail in Figure 3. As mentioned above, the tracking system provides an object's position (x,y) in a horizontal plane as well as its horizontal velocity vector (X,Y). If the object's perceived track speed is below a predefined level:

$$X^2 + Y^2 < Q1 \quad (1)$$

the object is considered to be moving too slowly to warrant attention and no further processing is performed. If however the object's track speed is above the predefined level Q1, processing continues by reorienting the entire coordinate system along the object's velocity vector to simplify subsequent calculations.

Figure 4 illustrates an object at 75 approaching a predefined polygonal region 79. The position of each

vertex (80-83) of the region 79 is initially defined by (a_i, b_i) coordinates. Upon reorienting this coordinate system along the object's velocity vector 77, centered at the object's position 75, each vertex is redefined as (A_i, B_i) while the object's position would necessarily be defined by $(0,0)$. This reorientation is accomplished as follows:

$$A_i = \frac{(a_i - x)X + (b_i - y)Y}{(X^2 + Y^2)^{\frac{1}{2}}} \quad i = 1, 2, \dots, n \quad (2)$$

$$B_i = \frac{(a_i - x)Y - (b_i - y)X}{(X^2 + Y^2)^{\frac{1}{2}}} \quad i = 1, 2, \dots, n \quad (3)$$

Once reoriented in this fashion it is a simple matter to determine whether an object is approaching or departing from the predefined region. A positive A_i indicates an approach while a negative A_i is indicative of the object's departure from the particular vertex. If:

$$A_i < 0 \text{ for all } i \quad (4)$$

then the object is moving away from the entire predefined region and no further processing is performed for such an object.

If however A_i is positive for even a single vertex and the object has sufficient speed (Equation 1) then the uncertainties associated with the tracking system's positional and velocity measurements for the approaching object are considered in determining whether an intrusion is likely.

A J parameter is calculated for each vertex using the vertex's reoriented coordinates (A_i, B_i) as well as the position variance (P), velocity variance (V) and position-velocity covariance (C) as follows:

$$J_i = \frac{B_i^2}{P + 2CA_i + VA_i^2} \quad i = 1, 2, \dots, n \quad (5)$$

The uncertainty of the object's positional and velocity measurements are interrelated in the denominator of Equation 5 and in effect serve to project an uncertainty zone 84 out in front of the moving object 78 as illustrated in Figure 5. A number of different combinations and permutations are then possible regarding the relationship of a particular predefined region relative to the uncertainty zone 84, i.e., the region can either lie wholly outside 85,86 or wholly inside 87 the zone 84. Alternatively, the region 88,89 can lie partly inside and partly outside the zone or the region 90 can wholly envelope the uncertainty zone. If:

$$J_i > Q_2 \text{ for all } i \quad (6)$$

wherein Q_2 is a predefined parameter and the sign of all B_i is the same, then the predefined region is located in a position generally depicted by either 85 or 86 in Figure 5. Such a situation is indicative of a "sure non-intrusion" and no further processing is performed for that object.

If on the other hand, if for any two vertices j and k :

$$J_j > Q_3 \quad (7)$$

$$J_k > Q_3 \quad (8)$$

wherein Q_3 is a predefined parameter and the sign of B_j does not equal the sign of B_k , the situation depicted by reference numeral 90 of Figure 5 is indicated, "sure intrusion" is therefore imminent and processing continues accordingly. For all other situations (87, 88, 89) a lateral intrusion may or may not occur and processing continues as appropriate for an "unsure intrusion".

The next step for either a sure intrusion 90 or an unsure intrusion (87, 88, 89) condition entails calculating the lateral entry time 93 of the approaching object 78 into the predefined polygonal region. This is accomplished by considering the vertex closest to the approaching object i.e. the smallest A_i which shall be designated A_j .

If $J_j < Q_3$ (see Equation 5), the closest vertex lies within the uncertainty zone 84 and:

$$T_1 = \max \left\{ 0, \frac{A_j}{S} \right\} \quad (9)$$

where S is the speed of the object:

$$S = (X^2 + Y^2)^{1/2} \quad (10)$$

If on the other hand, $J_j > Q3$, i.e., the closest vertex lies outside the uncertainty zone 84, and the next closest vertex, designated (A_k, B_k) the sign of B_k does not equal the sign of B_j , then:

$$T_1 = \max \left\{ 0, \frac{\frac{|B_L| A_k}{|B_L| + |B_k|} + \frac{|B_k| A_L}{|B_L| + |B_k|}}{S} \right\} \quad (11)$$

$$L = \begin{cases} k + 1 & \text{if } B_k > 0 \\ k - 1 & \text{if } B_k < 0 \end{cases} \quad (12)$$

If $J_j > Q3$ and the sign of B_k equals the sign of B_j , then:

$$T_1 = \max \left\{ 0, \frac{A_k}{S} \right\} \quad (13)$$

Once the lateral entry time T, has been estimated, it is compared to the minimum and maximum look-ahead time in the time decision check step 95 of Figure 2. The maximum look-ahead time $T_{\max}$ is a predefined parameter while the minimum look ahead time is the longer of either a predefined parameter Q4 based on the response time of an appropriate counter measure or a function of how quickly the approaching object can climb over the top of the predefined polygonal region:

$$T_{\min} = \max \left\{ Q4, T_\theta \right\} \quad (14)$$

$$T_{\theta} = \frac{h_{(T_1)} - HU}{S \tan \theta} \quad (15)$$

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Wherein $h_{(T_1)}$ is the predicted height of the approaching object at time T_1 , which is the predicted time of lateral entry. HU is the upper height limit of the predefined region and θ is a predefined escape climb rate parameter. In order to perform the above calculation, height and rate of height change must have been provided by the tracking system. If $T_1 > T_{\max}$ no alert is indicated. If $T_1 < T_{\min}$, processing continues towards the height final alert process 105. If T_1 is in between $T_{\min}$ and $T_{\max}$, then processing continues towards height decision alert process 103.

The time delay filter 97 is invoked when an unsure intrusion (87, 88, 89) had been indicated in the lateral intrusion determination 91. If $T_1 > T_{\min}$ then no alert is indicated. If $T_1 < T_{\min}$, processing continues on towards the height final alert process 105.

In the lateral final alert process 99, a decision whether to indicate an alert condition or not is made depending on whether missed detections are to be controlled at the expense of false alarms or vice versa. If missed detections are to be controlled at the expense of false alarms, and if:

$$J_i > Q7 \text{ for any } i \quad (16)$$

then processing continues. Otherwise no alert is issued. If on the other hand, false alarms are to be controlled at the expense of missed detections, a second predefined parameter Q8 is considered and if for any two indices j and k:

$$J_j > Q8 \quad (17)$$

$$J_k > Q8 \quad (18)$$

and the sign of B_j equals the sign of B_k then processing continues. Otherwise no alert is issued.

In order to determine whether an object will intrude into the predefined polygonal region by descending into the region from above, it is necessary to know both the entry time of lateral intrusion T_1 as well as the exit time of lateral intrusion T_2 . Generally, the knowledge that an approaching object is above the predefined region at the time of lateral entry does not preclude the possibility of an intrusion. It must therefore also be determined whether the approaching object still has sufficient altitude at the time the predefined polygonal zone is laterally exited. To that end, the lateral exit time T_2 is calculated 101 in a manner analogous to the calculation of the entry time T_1 93. The vertex furthest from the approaching object, i.e. the vertex with the largest A_i which shall be designated (A_m , B_m) is considered. If $J_m < Q9$ (a predefined parameter) then:

$$T_2 = \min \left\{ \frac{A_m}{S}, Q6 \right\} \quad (19)$$

Wherein Q6 is a predefined maximum time limit. If on the other hand, $J_m > Q9$ and the vertex therefore lies outside the uncertainty zone, the second furthest vertex, designated (A_n , B_n) is considered. If, the sign of B_m does not equal the sign of B_n , then:

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$$T_2 = \min \left\{ \frac{|B_p| |A_n|}{|B_p| + |B_n|}, \frac{|B_n| |A_p|}{|B_p| + |B_n|}, Q6 \right\} \quad (20)$$

wherein:

$$P = \begin{cases} n - 1 & \text{if } B_n > 0 \\ n + 1 & \text{if } B_n < 0 \end{cases} \quad (21)$$

If $J > Q9$ and the sign of B_m equals the sign of B_n , then:

$$T_2 = \min \left\{ \frac{A_n}{S}, Q6 \right\} \quad (22)$$

Once both T_1 and T_2 are known in addition to the previously provided height h and height rate H data, the height variance HP , height rate variance HV and height-height rate covariance HC are considered in conjunction with the upper height limit HU and lower height limit HL to provide the final decisions regarding the potential for intrusion.

In the height decision alert process two more parameters need be calculated:

$$E_1 = Q10 (HP + 2HC \cdot T_1 + HV \cdot T_1^2)^{1/2} \quad (23)$$

$$E_2 = Q11 (HP + 2HC \cdot T_2 + HV \cdot T_2^2)^{1/2} \quad (24)$$

wherein $Q10$ and $Q11$ are predefined parameters. An alert will be issued if any of the following four conditions (equations 25-28) are satisfied:

$$HL + E_1 < h + H \cdot T_1 < HU - E_1 \quad (25)$$

$$HL + E_2 < h + H \cdot T_2 < HU - E_2 \quad (26)$$

$$h + H \cdot T_1 \geq HU - E_1$$

and

$$h + H \cdot T_2 \geq HL - E_2 \quad (27)$$

$$h + H \cdot T_1 \geq HL - E_1$$

and

$$h + H \cdot T_2 \geq HU - E_2 \quad (28)$$

otherwise no alert will be issued.

If, on the other hand, the approaching objects $T_1 < T_{min}$, whether a sure intrusion or an unsure intrusion, an alert will be issued at 105 if any of the following conditions (equations 29-32) are satisfied:

$$HL < h + H \cdot T_1 < HU \quad (29)$$

$$HL < h + H \cdot T_2 < HU \quad (30)$$

$$h + H \cdot T_1 \geq HU$$

and

$$h + H \cdot T_2 \leq HL \quad (31)$$

$$h + H \cdot T_1 \leq HL$$

and

$$h + H \cdot T_2 \geq HU \quad (32)$$

otherwise no alert will be issued.

Once an alert has issued, and as an object's position and trajectory can be more precisely be predicted, the alert is turned off if a lateral sure non-intrusion is indicated (Equations 7 & 8) or if either of the following conditions regarding the approaching objects height dynamics are indicated:

$$HL - E_1 > h + H \cdot T_1$$

and

$$HL - E_2 > h + H \cdot T_2 \quad (33)$$

$$HV + E_1 < h + H \cdot T_1$$

and

$$HU + E_2 < h + H \cdot T_2 \quad (34)$$

In operation, the system and methods of the present invention are employed in conjunction with a tracking system which is capable of supplying positional as well as dynamic data for a plurality of moving objects. In addition, the perimeter of the predefined polygonal zone is precisely known. The first consideration made is whether a particular object is moving fast enough and in fact toward the predefined polygonal zone. Each object that survives these two considerations then in effect has an uncertainty region projected along its velocity vector. The predefined polygonal zone is then considered in relation to the uncertainty region and depending on its positional relationship the determination whether a sure intrusion exists, a sure non-intrusion exists, or an unsure intrusion is indicated can then be made. If an intrusion is possible, the time for lateral entry and exit is calculated after which the height position and dynamics are taken into consideration. The various parameters employed in the various calculations and determinations are selected according to the requirements of a specific installation. Appropriate adjustment of the values of these various parameters will ultimately determine whether tracking errors will tend to yield false alarms or undetected intrusions.

While a particular form of the invention has been illustrated and described, it will also be apparent to those skilled in the art that various modifications can be made without departing from the spirit and scope of the invention. Accordingly, it is not intended that the invention be limited except as by the appended claims.

Claims

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- 1.A system for providing an early warning of imminent intrusion by a tracked moving object (78) into a predefined three-dimensional polygonal zone (79), such Zone's periphery being defined by its projection onto a two-dimensional plane and its maximum height above said plane, characterized by:
means for ascertaining apparent position (75) and velocity (77) of such object as projected onto such plane,
in addition to variances and a covariance associated with said apparent position and velocity;
means for extending out in front of said moving object's apparent position along such plane, an uncertainty region (84) indicative of possible future positions of such object based on said ascertained position, velocity, variances and covariance;
means for determining whether such object moving within said uncertainty region could cross through such predefined polygonal zone as projected onto such plane;
means for calculating an earliest possible entry time for such object moving within said uncertainty region on such plane into said projection of such predefined polygonal zone;
means for calculating a latest possible exit time for such object moving within said uncertainty region on such plane from said projection of such predefined polygonal zone;
means for ascertaining such object's height and rate of height change above such plane, in addition to variances and covariances associated with said height and rate of height change;
means for predicting possible future heights of such object based on said ascertained height, rate of height change, variances and covariance;
means for predicting when such object's height could fall below such polygonal zone's maximum height;
means for determining whether a predicted height below such predefined polygonal zone's maximum height occurs after said calculated earliest possible entry time and before said calculated latest possible exit time thereby indicating an intrusion; and
means for issuing an alert when said intrusion could occur within a predefined period of time.
2. The system of Claim 1 wherein such polygonal zone's (79) periphery is more particularly defined by vertices (80, 81, 82, 83) of said projection onto said two-dimensional plane.
3. The system of claim 2 further providing means for ceasing all further processing if it is determined that said apparent velocity of such object is below a predefined limit, if such object moving within said uncertainty region could not cross through such predefined polygonal zone as projected onto such plane, or if said calculated earliest possible entry time exceeds a predefined value.
4. The system of Claim 2 further comprising means for determining whether the crossing of such object through such predefined polygonal zone is sure to occur.
5. The system of Claim 4 wherein said means for issuing an alert is invoked within a shortened predefined period of time when it has been determined that the crossing of such object through such predefined polygonal zone is sure to occur.
6. The system of Claim 2 wherein such two-dimensional plane defines the horizontal.
7. The system of Claim 1 wherein the means for ascertaining apparent position comprises a radar system and the means for determining apparent velocity comprises a computing means which computes changes of said apparent position as a function of time.

8. The system of Claim 2 further comprising a means for displaying such object's position and indicating an alert issued therefor.

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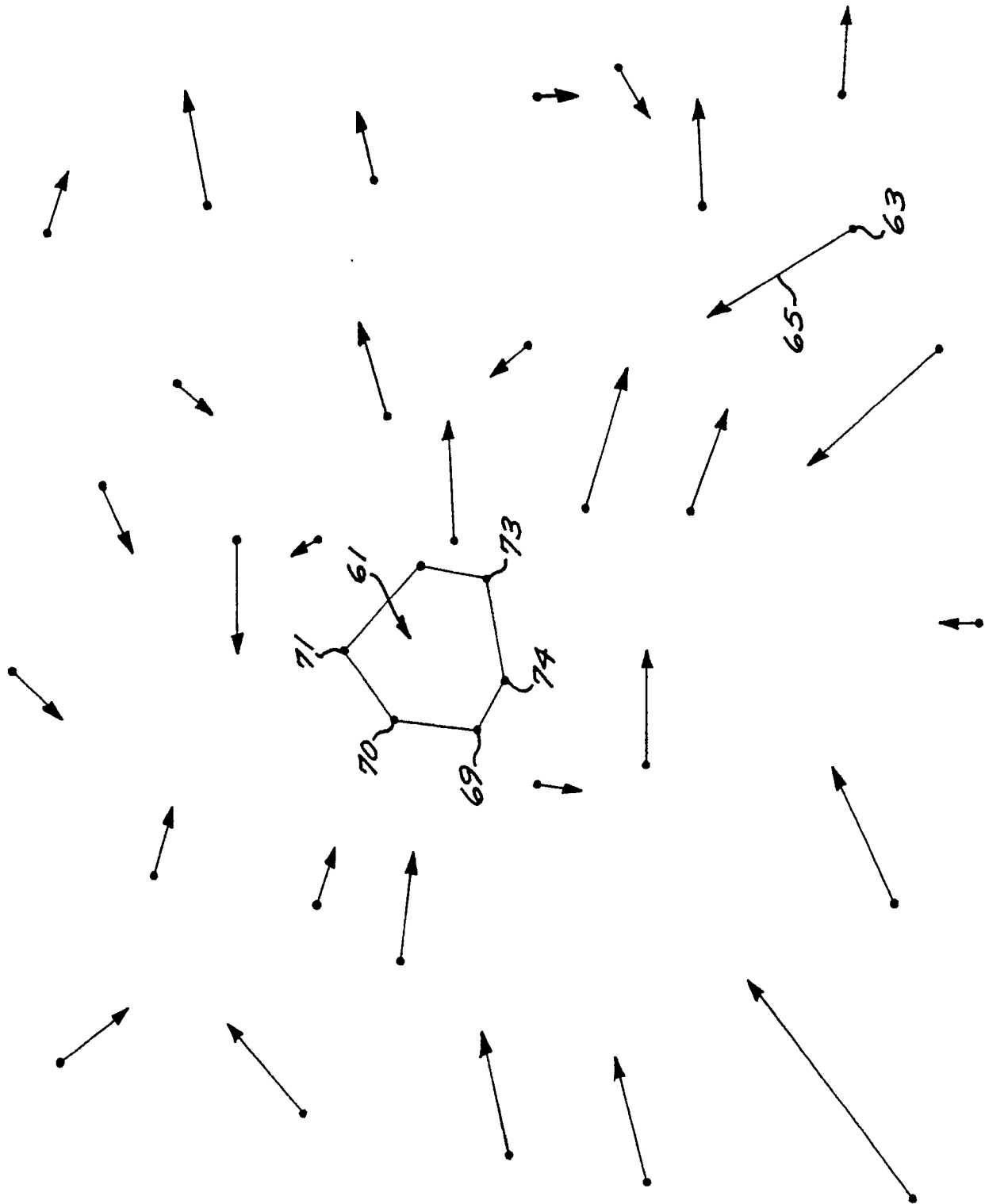


FIG. 1

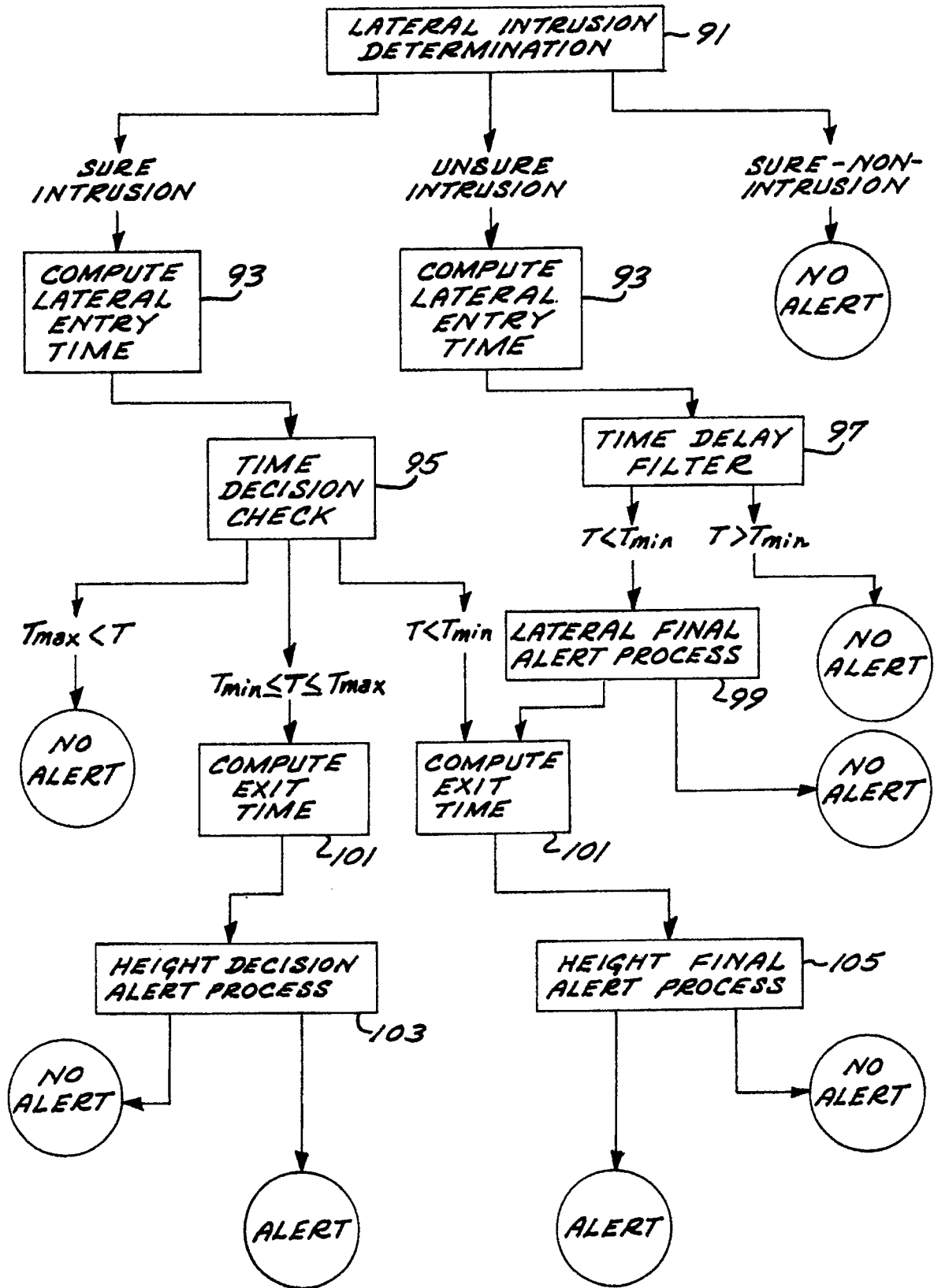


FIG. 2

LATERAL DECISION
ALERT PROCESS

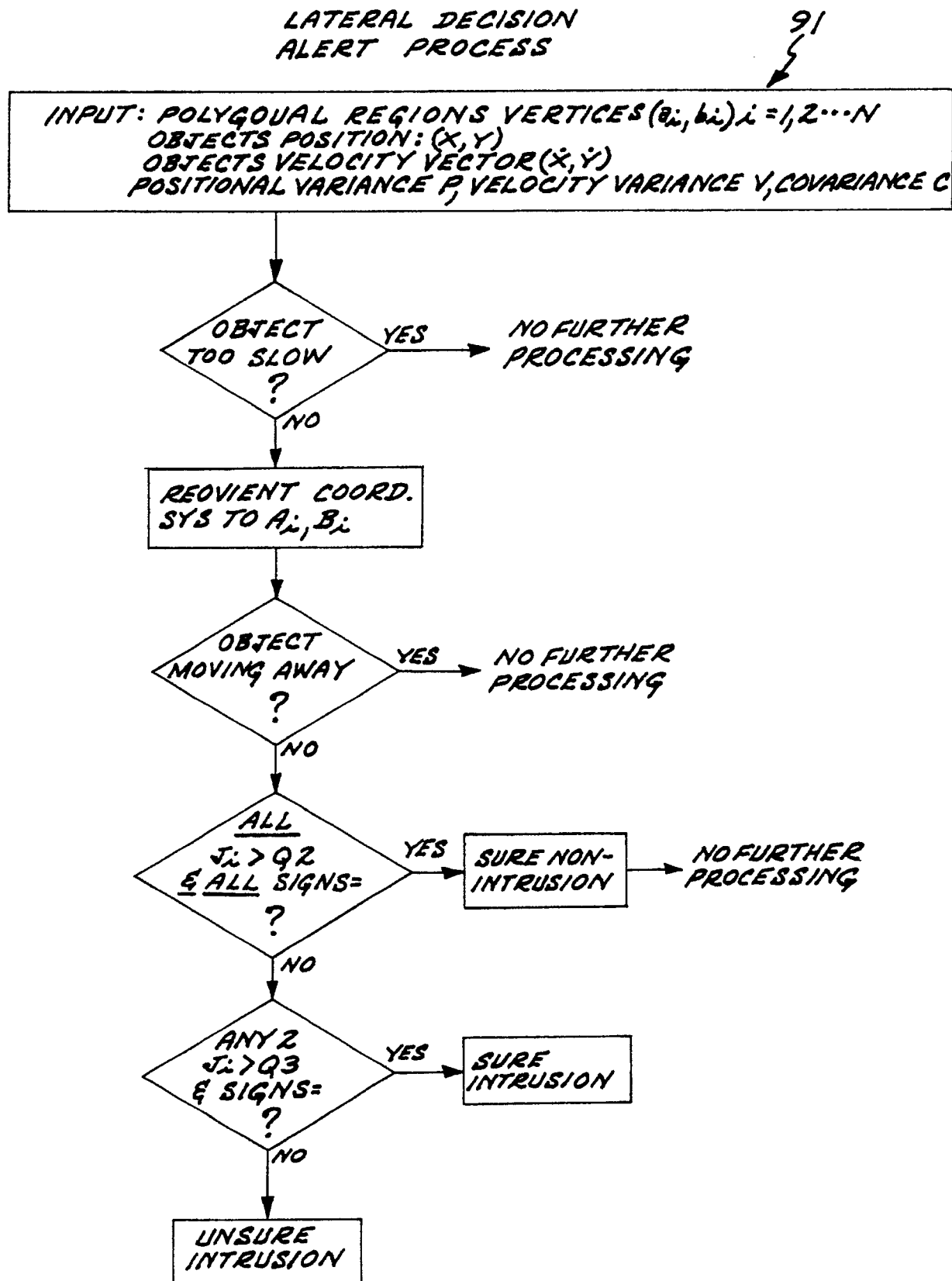


FIG.3

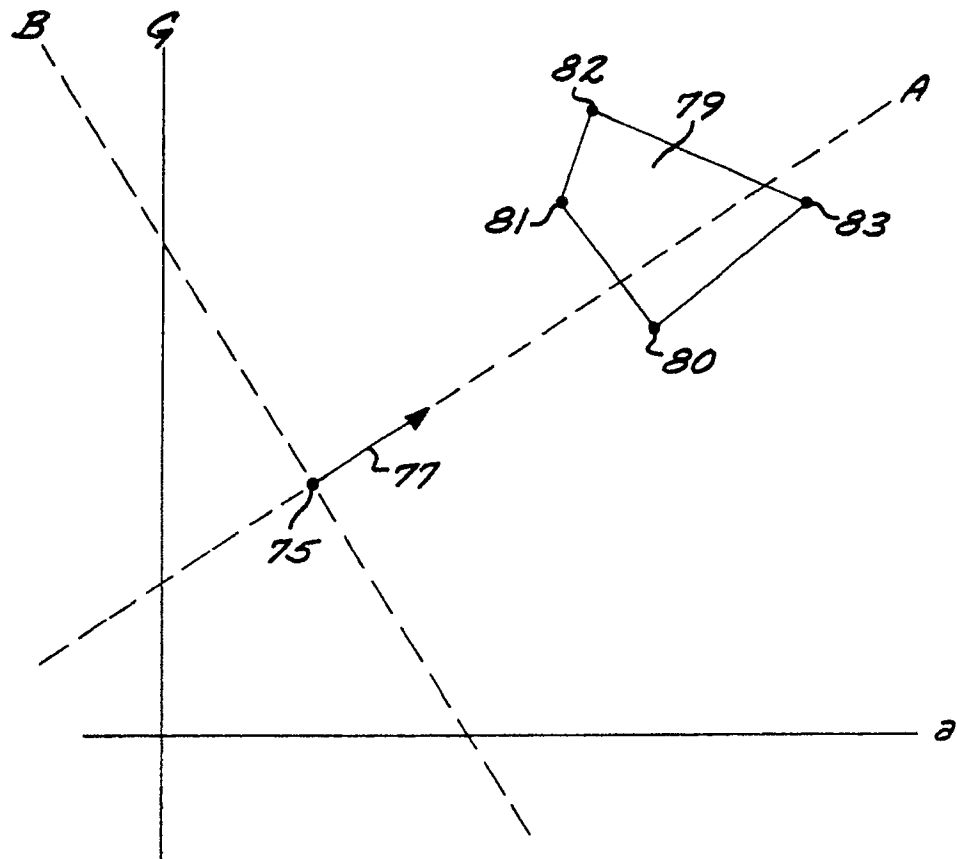


FIG. 4

FIG. 5

