Exploration of Two Position Adjustment Methods for Underground Mine Tracking Systems

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BIOGRAPHY

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Mr. David Snyder is a Senior Mine Electrical Engineer with the NIOSH Office of Mine Safety and Health. He is responsible for the research and development of communications and tracking systems for underground coal mines. Prior to joining NIOSH, Dave had more than 20 years experience in wireless telecommunications research, development, and engineering. Earlier in his career, Dave worked as a mining engineer for operators in the central Pennsylvania coal fields including Bethlehem Mines. He has a B.S. degree in Mining Engineering from Penn State University, an M.S. degree in Electrical Engineering from George Washington University, and he is a registered Professional Engineer.

Mr. Nicholas Damiano is an electrical engineer at Pittsburgh Research Lab, CDC/NIOSH. Graduating from the University of Pittsburgh with a B.S.E.E. in 2002, Nick worked for Allegheny Energy, a local power distribution company, before entering civil service with the U.S. Dept. of Labor, Mine Safety and Health Administration in Pittsburgh as an accident investigator for Technical Support there. He has more than seven years of combined experience in the electrical field including computers, power systems, and digital signal processing.

ABSTRACT

Currently many underground coal mines worldwide have installed or been planning to install a tracking system to trace miners mainly for their safety. Although many systems have been reported functional, a lack of sophisticated and systematic error correction methods apparently is still an issue for them; often it results in a low system resolution. To improve the system resolutions, this paper introduces two position adjustment methods for mine tracking systems. The first is an entry-matching method that optimally adjusts an off-course tracking device to the closest tunnel (entry). The second is a distance measurement adjustment method that accurately adjusts the position of a tracking device along an entry according to a measured distance from the device to a reference point. The coplanar node-path network mine model is used as the foundation for the development of these two methods.

INTRODUCTION

Mine tracking systems are used to locate miners in underground coal mines during normal operations and in an emergency. Several types of mine tracking systems have been developed and many systems have been put into service worldwide. Among them are RFID (radio frequency identification), inertial-based, and radio node-based systems. A RFID system determines the location of a miner using a stationary reader at a known location to scan a RFID tag worn by a miner within its range. An inertial tracking system relies on its own inertial measurement unit (IMU) to attain the data and complete its own location calculations. A node-based system uses the communication linkage of a stationary transceiver (node) and a mobile transceiver (tracking device) to estimate the relative location of the device. Although current tracking systems are functional, none seems capable of correcting for some common errors, such as a tracking device reporting itself inside a solid coal body.

This paper presents two systematic position adjustment methods. The first is an entry-matching method that corrects errors by repositioning a tracking device that is reporting itself outside an entry to a location in the closest entry. The second is a distance measurement adjustment method that accurately adjusts the current position of a tracking device with a given distance to a reference location along the entries.

MINE MODEL

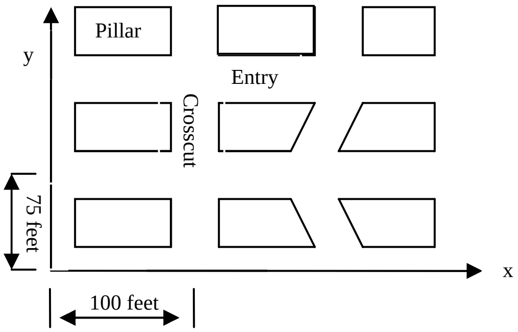
The mine model is the foundation for the position adjustment methods. The underground coal mine is modeled as a coplanar node-path network of its tunnels. The main tunnels in the mine are called “entries.” These main entries are intersected by other tunnels which are called “crosscuts.” Only the length of the entries and crosscuts are considered in the network model — their widths, heights and undulations are ignored.

The center lines of the entries and crosscuts are mapped onto an x-y plane as the network paths, and the intersections of the entries and crosscuts are the network nodes. A curved entry or crosscut is modeled as a series of line segments. Thus, every entry and crosscut is unambiguously identifiable by one or more line segments (paths). Every intersection can be identified by the matching of the endpoints of two or more line segments (nodes). The location of a tracking device is identified by its unique (x, y) coordinates on the plane.

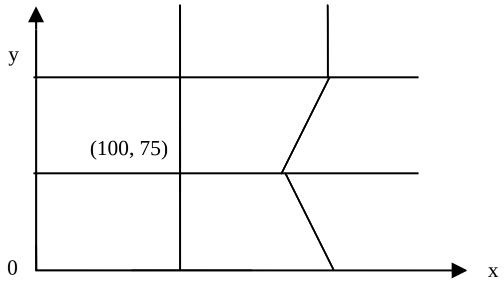
The origin of the x-y coordinates for the mine’s node-path network can be set anywhere in the plane. The line segments representing all entries and crosscuts become deterministic once an x-y plane is selected for a mine. The selections of the scales of the x and y axes are also arbitrary. Mine entries can be mapped onto the plane in their actual or scaled-down lengths.

Figure 1 displays a portion of a mine to illustrate the node–path network. Figure 1 (a) shows a selected x-y coordinate system superimposed onto the mine map with a scale of 1:1. Figure 1 (b) displays only the mine’s node-path network.

There are several essential operational restrictions on the mine’s node-path network. A mobile tracking device is only allowed to enter the network from predetermined fixed points. It must move continuously along and stay on the existing line segments. Under ordinary operation, no tracking device is allowed to enter the node-path network at another arbitrary point, jump from one point to another, or jump from one line segment to another. A tracking device must be at a point somewhere on a line segment. These restrictions are based on the reality that a mine has only limited entrances available for any tracking device to enter or exit the mine, and the mine entries and crosscuts are the only free space for them to travel. These restrictions are used in the procedure development of the position adjustment methods.



(a) **Axes are superimposed on a mine map**



(b) **Entry line segments on x-y plane**

Figure 1: Node-path network of a mine on the x-y plane

TWO POSITION ADJUSTMENT METHODS

The first method, the entry-matching method, is based on restrictions on the tracking devices in the mine’s node-path network, and can be used to bring a tracking device back to the network if the device is off-track. The second method, the distance measurement adjustment method, is based on a measured distance between a stationary reference location and the tracking device. This method is particularly suited for a node-based tracking system.

Entry-matching Method

The entry-matching method brings an off-the-line tracking device to the closest entry, and it can be used in a variety of tracking systems for error correction. It can also be used as a damping procedure to minimize the drift effects of the IMU in an inertial tracking system.

Two assumptions are made in the implementation of this method. The first is that the tracking system is able to save and retrieve the position value of each of its tracking devices obtained in the previous calculation. The previous position value will be referenced in determining the current optimal position of a tracking device. The second assumption is that a mapping tool, which is not included in this paper, has already mapped a real three dimensional (3-D) location of a tracking device in the mine to a (x_i, y_i) location, called an initial mapped location (IML), on the mine's plane prior to implementation of this method. The entry-matching method starts with the IML (x_i, y_i) and ends with an optimal current location (x_c, y_c) on the mine's coplanar x-y plane.

This method covers three different IML outcomes resulting from mapping a real 3-D location of a tracking device onto the x-y plane. The first outcome is that the IML (x_i, y_i) falls on the same entry or line segment with the previously saved position (PSP) in the last step, as shown in Fig. 2. The IML is, in this case, regarded as the optimal current position (x_c, y_c). The system simply updates its position with the IML (x_i, y_i) values, and moves on to the next round of position adjustments. Equation (5) can be used to determine whether two points share the same entry or line segment on the x-y plane.

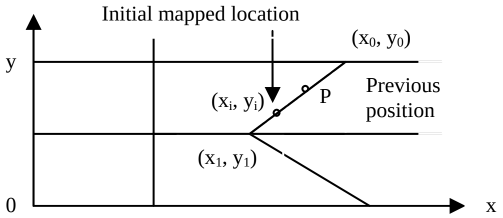


Figure 2: IML and PSP share the same line segment

The second outcome is that the IML of a tracking device is near the PSP but off any entry course or line segment on the x-y plane. One example is the device reports its position inside a coal body. As stated before, this is not allowed. The IML needs to be adjusted to the optimal location on an entry. The optimal current position of a tracking device is the closest point from the IML to the closest entry or line segment. The following is a general approach to obtain such an optimal position. The tracking system first draws, from its IML, perpendicular lines to all of the line segments located near the IML on the x-y plane. The system then identifies, among all of the perpendicular lines, the one with the shortest distance from the IML. The intersection to that line segment will be regarded as the current optimal position (x_c, y_c) of the tracking device, as shown in Fig. 3, where the dotted lines are the perpendicular lines. The tracking system then updates and saves the location value.

Next is the introduction of steps to obtain an intersection on a line segment by a perpendicular line, and the distance between the IML and that line segment. The line segment with two endpoints of (x_0, y_0) and (x_1, y_1), shown in Fig. 3, is used as an illustration of these steps. The first step is to find the slope of that line segment using (1).

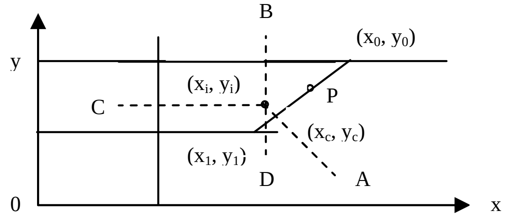


Figure 3: Find an optimal position from IML

$$a = \begin{cases} 0 & \text{if } y_0 - y_1 = 0 \\ (y_0 - y_1)/(x_0 - x_1) & \text{if } x_0 - x_1 \neq 0 \\ \infty & \text{if } x_0 - x_1 = 0 \end{cases} \qquad (1)$$

The second step is to obtain the intersection (x_c, y_c) from the IML to that line segment using (2). Note: there are many different ways to calculate the intersection; we are suggesting one of them.

$$\begin{bmatrix} x_c \\ y_c \end{bmatrix} = \begin{cases} \begin{bmatrix} x_i \\ y_0 \end{bmatrix} & \text{for } a = 0 \\ \begin{bmatrix} \dfrac{a^2 x_0 - a y_0 + x_i + a y_i}{1 + a^2} \\ \dfrac{a x_i + a^2 y_i - a x_0 + y_0}{1 + a^2} \end{bmatrix} & \text{for } 0 < a < \infty \\ \begin{bmatrix} x_0 \\ y_i \end{bmatrix} & \text{for } a = \infty \end{cases} \qquad (2)$$

The third step is to calculate the distance (*D)* between the IML (x_i, y_i) and the intersection (x_c, y_c) on the perpendicular line A on Fig. 3 using (3). Note: there are many different ways to calculate the distance; we are suggesting one of them.

$$D = \begin{cases} |y_i - y_0| & \text{for } a = 0 \\ \left| \dfrac{a(x_0 - x_i) + (y_i - y_0)}{\sqrt{1 + a^2}} \right| & \text{for } 0 < a < \infty \\ |x_0 - x_i| & \text{for } a = \infty \end{cases} \qquad (3)$$

Similarly, lines B, C, and D are drawn perpendicular to the rest of the surrounding line segments from the IML (x_i, y_i) as shown in Fig. 3. The intersections of these surrounding line segments and the distances to those segments from the IML can again be obtained using (1), (2), and (3). Evidently, in this example, the shortest distance is from the IML (x_i, y_i) to the intersection (x_c, y_c) on line A. The intersection (x_c, y_c) is selected as the current optimal tracking device position as it shares the same line segment with the PSP, P on Fig. 3.

If the IML (x_i, y_i) has the same short distances to two separate line segments, as shown in Fig. 4, the tracking system refers to its PSP, P, to determine the current position of the tracking device. In this example, the position (x_c, y_c) will be selected as the tracking device's optimal position because it has the shortest distance to the PSP, P, from the last step.

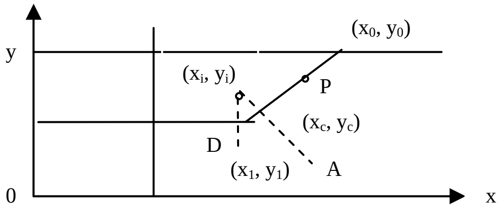


Figure 4: IML has the same distance to two line segments

The third outcome is when the IML (x_i, y_i) is farther away from the PSP, P, as shown in Fig. 5. To prevent the tracking device from executing a sudden long jump from one line segment to another, or from one entry to another, the tracking system may try to find an average location over a number of initial mapped locations, and then determine its current optimal (x_c, y_c) position. Equation (4) can be used to calculate an average initial location value, (x_{ai}, y_{ai}), where *n* is the total number of the initial mapped locations. The average initial location value can then be used to find an optimal current position on the closest entry. After that, the process moves on to the next round position adjustments.

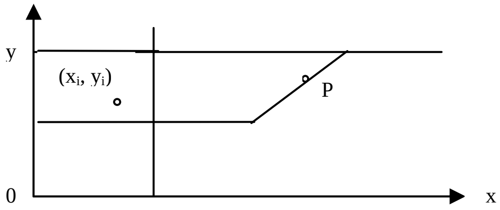


Figure 5: IML is too far from PSP

$$\begin{bmatrix} x_{ai} \\ y_{ai} \end{bmatrix} = \begin{bmatrix} (x_{i1} + x_{i2} + \ldots + x_{in})/n \\ (y_{i1} + y_{i2} + \ldots + y_{in})/n \end{bmatrix} \qquad (4)$$

$\textit{where } x_{ai} \textit{ and } y_{ai} : \textit{the average values}; x_{i1},\ x_{i2}, \cdots x_{in} \textit{ and}$
$y_{i1}, y_{i2} \cdots y_{in} : \textit{initial mapped values};\ n : \textit{the number of}$
the initial mapped locations of the tracking device.

Distance Measurement Adjustment Method

This method can be applied to those systems that provide an estimated distance along the entries between a known reference point and the tracking device. A node-based tracking system is an example of a system that uses the communication linkage of a stationary transceiver (node) and a mobile transceiver (tracking device) to estimate the radio path distance between them. An inertial tracking system can also use this method to correct its tracking device if its on-board IMU is capable of "remembering" a distance to a reference location and turning points along its moving path.

The fundamental assumptions with this method are that the radio signals travel only along the entries, and the strongest signal received by a tracking device always follows the shortest path. In some node-based tracking systems, a tracking device estimates the distance a signal travels from a stationary transceiver node by detecting received radio signal strengths. In other systems, a tracking device calculates the distance between itself and a node using the radio signal traveling time.

In general, there exist many paths from a node to a tracking device. Fig. 6 gives an example of signal paths shown by the dotted lines from the node to the tracking device receivers. In the figure, N represents the transceiver node and R_1, R_2, and R_3 represent tracking device receivers.

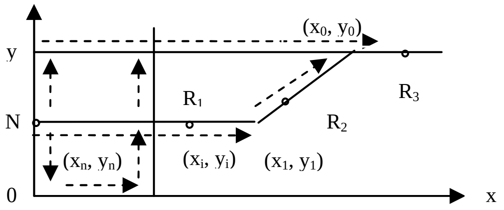


Figure 6: Node transmits navigation signal to receivers

For convenience in the following discussion, we assume that a node under discussion transmits a navigation signal that includes two parts; a timing signal and the current position of the node. After receiving the signal, a receiver calculates the signal traveling time and the signal traveling distance (STD), *D*, from the node, and adjusts its position according to the STD. The initial position, (x_i, y_i), of a receiver on a line segment must already be known before this method can be used. The distance measurement adjustment method starts with the initial position (x_i, y_i) and ends with an updated position (x_c, y_c) of the receiver on the receiver's line segment.

In an underground mine environment, the radio signals from a node may turn around the corner of a solid coal pillar before reaching a receiver as shown in Fig. 6. The figure also shows that the signal from node N may follow multiple paths to its receivers, and some of the paths may have one or more turns. The STD, *D*, can not be immediately used to complete the receiver's location computations if the signal path is not straight. The tracking system solves for its receiver's actual location by finding the shortest path to the node with the minimum number of turns among all possible radio signal paths. In most underground mine environments, the fewer turns a path has, the shorter the path is.

There are three typical signal paths that are covered in the second method, and they only differ in the number of turns each one has. As shown in Fig. 6, the first one is the signal path from the node (N) to the receiver (R_1), which has no turns. The second is the signal path from the node (N) to the receiver (R_2), which has only one turn at (x_1, y_1). The third is the signal path from the node (N) to the receiver (R_3), which has two separate turns at (x_1, y_1) and (x_0, y_0). The system will take the path with the least number of turns.

The process starts with a search of a straight path from a node to a receiver. It examines whether a node and a receiver share the same line segment slope and endpoints. A generalized case is shown in Fig. 7 where (x_n, y_n) and (x_i, y_i) are the node position and the initial receiver position respectively. If one of the conditions in (5) is satisfied, the node and the receiver or, any two points on the x-y plane, should be on the same straight line segment.

$$a = \frac{y_n - y_0}{x_n - x_0} = \frac{y_i - y_0}{x_i - x_0} \quad \text{for } x_n - x_0 \neq 0 \text{ and } x_i - x_0 \neq 0 \tag{5a}$$

$$a = \frac{y_n - y_0}{x_n - x_0} = \frac{y_i - y_1}{x_i - x_1} \quad \text{for } x_n - x_0 \neq 0 \text{ and } x_i - x_1 \neq 0 \tag{5b}$$

If the slope, *a*, of a line segment is infinite, the receiver only needs to check whether it shares the same line segment endpoints with the node line segment. If so, the node and the receiver are on the same line segment or entry.

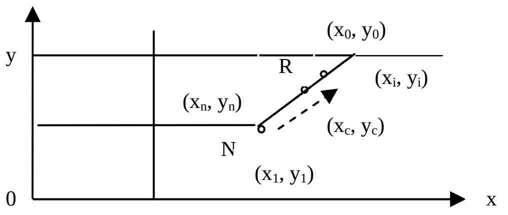


Figure 7: Node and receiver are on the same line segment

When the node and the receiver are on the same line segment, the position of the receiver can be simply adjusted using the STD, *D*, from the node along the line segment. With the calculated slope, *a*, the receiver's current position can be calculated from one of the equations in (6). The following criteria can be used to select a correct equation in (6). I) if $a \geq 0$, and $y_i \geq y_n$ and $x_i \geq x_n$, use (6*a*); II) if $a \leq 0$, and $y_i \geq y_n$ and $x_i \leq x_n$, use (6*b*); III) if $a \geq 0$, and $y_i \leq y_n$ and $x_i \leq x_n$, use (6*c*); IV) if $a \leq 0$, and $y_i \leq y_n$ and $x_i \geq x_n$, use (6*d*); V) if $a = \infty$, and $y_i \geq y_n$, use (6*e*);) if $a = \infty$, and $y_i < y_n$, use (6*f*). After that, the process moves on to the next round of receiver position adjustments.

$$\begin{bmatrix} x_c \\ y_c \end{bmatrix} = \begin{cases} \begin{bmatrix} x_n + D/\sqrt{1+a^2} \\ y_n + (aD)/\sqrt{1+a^2} \end{bmatrix} & (6a) \\ \quad \text{for } a \geq 0,\ y_i \geq y_n \text{ and } x_i \geq x_n & \\ \begin{bmatrix} x_n - D/\sqrt{1+a^2} \\ y_n + (aD)/\sqrt{1+a^2} \end{bmatrix} & (6b) \\ \quad \text{for } a \leq 0,\ y_i \geq y_n \text{ and } x_i \leq x_n & \\ \begin{bmatrix} x_n - D/\sqrt{1+a^2} \\ y_n - (aD)/\sqrt{1+a^2} \end{bmatrix} & (6c) \\ \quad \text{for } a \geq 0,\ y_i \leq y_n \text{ and } x_i \leq x_n & \\ \begin{bmatrix} x_n + D/\sqrt{1+a^2} \\ y_n - (aD)/\sqrt{1+a^2} \end{bmatrix} & (6d) \\ \quad \text{for } a \leq 0,\ y_i \leq y_n \text{ and } x_i \geq x_n & \\ \begin{bmatrix} x_n \\ y_n + D \end{bmatrix} \quad \text{for } a = \infty, \text{ and } y_i \geq y_n & (6e) \\ \begin{bmatrix} x_n \\ y_n - D \end{bmatrix} \quad \text{for } a = \infty, \text{ and } y_i \geq y_n & (6f) \end{cases}$$

The process will be programmed to search for a path with one turn after the above search for a zero-turn path fails. Fig. 8 shows a generalized case where the signal path has a turn at (x_4, y_4) from the node (N) at (x_n, y_n) to the receiver (R). The receiver's initial position is at (x_i, y_i).

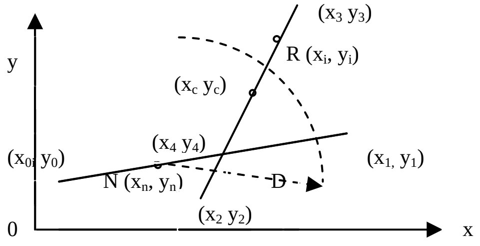


Figure 8: Node and receiver segments share an intersection

As shown in Fig. 8, (x_0, y_0) and (x_1, y_1) are the endpoints of the node line segment; (x_2, y_2) and (x_3, y_3) are the endpoints of the receiver line segment. The intersection of the two line segments is (x_4, y_4). The location of the node (x_n, y_n) is already known from the navigation signal. A circle is then drawn at (x_n, y_n) with the radius of the STD, *D*, to confine the search area. Any potential signal path shall fall within the circle because the STD is the longest distance for any possible signal path. Within the circle, the receiver tries to determine whether there exists a path from itself to the node through an existing intersection in the following steps.

1) Referring to Fig. 8, use (7*a*) to obtain the slope of the node line segment, and then use (7*b*) to obtain the slope of the receiver line segment.

$$a_n = (y_1 - y_0)/(x_1 - x_0) \tag{7a}$$

$$a_r = (y_3 - y_2)/(x_3 - x_2) \tag{7b}$$

2) Calculate an intersection (x, y) of these two line segments using (8). The calculated intersection will be the actual intersection if it already exists on both line segments, or it will be the calculated intersection of the extension of both lines to where they meet. The latter indicates that these line segments have no actual common connection (not shown in Fig. 8).

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \dfrac{a_n x_n - y_n - a_r x_i + y_i}{a_n - a_r} \\ \dfrac{a_n y_i - a_n a_r x_i + a_n a_r x_n - a_r y_n}{a_n - a_r} \end{bmatrix} \tag{8}$$

3) Use the inequality (9) to check whether the calculated intersection (x, y) from (8) is within the STD, *D*. The intersection is valid only if equation (9) is satisfied.

$$(x - x_n)^2 + (y - y_n)^2 < D^2 \tag{9}$$

4) Determine whether the calculated intersection already exists on both the node and receiver line segments by checking whether its (x, y) coordinates satisfy every inequality in (10). The intersection is an actual turning point of the signal path only if the checking passes (10).

$$\begin{aligned} &\min(x_0, x_1) \le x \le \max(x_0, x_1) \\ &\min(y_0, y_1) \le y \le \max(y_0, y_1) \\ &\min(x_2, x_3) \le x \le \max(x_2, x_3) \\ &\min(y_2, y_3) \le y \le \max(y_2, y_3) \end{aligned} \tag{10}$$

The path with a single turn can be confirmed only after steps 3 and 4 are passed (Ideally, it should have x = x_4, and y = y_4). Repeat the same procedures to determine all other paths between the node and the receiver within the circle.

All paths start from node position (x_n, y_n). The next phase is to determine the ends of the paths using the following three steps.

1) Find the distance from the node (x_n, y_n) to the intersection (x_4, y_4) using (11).

$$D_{n-4} = \sqrt{(x_4 - x_n)^2 + (y_4 - x_n)^2} \tag{11}$$

2) Find the partial STD from point (x_4, y_4) to the receiver along the receiver line segment using (12).

$$D_{r-4} = D - D_{n-4} \tag{12}$$

3) As shown in Fig. 8, the partial signal path from (x_4, y_4) to (x_i, y_i) is a straight line segment, and the procedures introduced earlier in finding a zero-turn path can be used to calculate the path end point (x_c, y_c) as follows. Substitute *D* with D_{r-4}, x_n with x_4, and y_n with y_4 in equation (6). Then use it to calculate the point (x_c, y_c).

After all of the paths with their (x_c, y_c) end points are obtained, the one with the shortest distance to the receiver's initial position (x_i, y_i) will be used as the real signal path. The receiver can update its position with that path's end point accordingly. The process then moves on to the next round of the position adjustments.

The process will search for a signal path with two turns if the above search for a one-turn path fails. This case is shown in Fig. 9 where the signal path, which is from the node (N) at (x_n, y_n) to the receiver (R), has turns at (x_4, y_4) and (x_7, y_7). (x_i, y_i) is the initial position of the receiver.

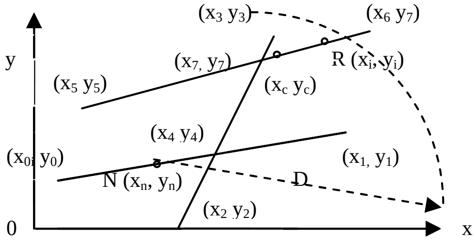


Figure 9: Node and receiver line segments share the third line segment

Although Fig. 9 gives only one signal path, multiple paths between the node and the receiver may exist, and all of them need to be identified. The shortest one among them is regarded as the actual path. The following procedures can be used to identify a path. Please refer to Fig. 9 for symbols.

1) First, draw a circle at the center of the node position (x_n, y_n) in the radius of the STD, *D*. The search for every path begins from the center. Every (x, y) point of every possible path must satisfy the condition confined by equation (13). Again, this is because the STD is the longest distance for any possible path.

$$D^2 \ge (x - x_n)^2 + (y - y_n)^2 \tag{13}$$

2) Now, use the following criteria to determine the initial path's search direction along the node's line segment. Start from the right if $x_i \geq x_n$, where x_i is the initial x coordinate value of the receiver, otherwise start from the left (if $x_i < x_n$). Similarly start from the upper direction if $y_i \geq y_n$, otherwise start from the down direction (if $y_i < y_n$). In the example shown in Fig. 9, the search path should obviously start from the right because $x_i > x_n$. Then find the nearest intersection along the node line segment. It is (x_4, y_4) in this example. Calculate the distance between (x_n, y_n) and (x_4, y_4) using equation (14) if (x_4, y_4) is in the circle and satisfies equation (13).

$$D_{n-4} = \sqrt{(x_4 - x_n)^2 + (y_4 - x_n)^2} \tag{14}$$

3) Calculate the partial STD from (x_4, y_4) to (x_i, y_i) using equation (15).

$$D_{r-4} = D - D_{n-4} \tag{15}$$

Then draw another circle at (x_4, y_4) with radius of $D_{r\text{-}4}$; the possible position of the receiver should be located within both the new and the old circles as shown in Fig. 10. As a result of the drawing of the second circle at the center of (x_4, y_4), the partial signal traveling path from (x_4, y_4) to (x_i, y_i) apparently has only one turn at (x_7, y_7). The procedures for searching for a path with a single turn introduced earlier can be applied to find a path from (x_4, y_4) to the receiver.

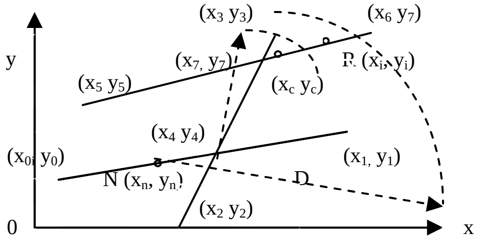


Figure 10: The second circle is drawn at (x_4, y_4) with radius $D_{r\text{-}4}$

Repeat this procedure and find all other possible paths from the node to the receiver within the initial circle. Then identify the shortest path among them. It is useful to note that the number of turns with a path is equal to the number of the circles drawn in the above path-finding procedure.

This method searches for the shortest path starting with the least number of turns. Evidently, the core parts of this method are those used to calculate the current position of a receiver along the straight path. Through the repeated turn-eliminating process, the paths with one or more turns all have their partial straight lines remaining, and the core parts then are used for completion of the position calculations. This nested process could be used to create a program with a small footprint on computer memory for an actual system.

SUMMARY

This coplanar node-path network model of an underground coal mine can be used in the development of more accurate position adjustment methods for tracking systems. In this model, the entire mine entry network can be digitally mapped onto an electronic coplanar network that can be displayed on a self-updating computer monitor. The two methods presented are examples of using the model to make more accurate position calculations. The increased accuracy can greatly improve the chances of precisely locating individuals in need and reduce the time rescue teams need to locate them.

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