TIME DOMAIN®

PulsON® 400 Ranging & Communications

Part Four: Tracking Architectures Using Two-Way Time-of-Flight (TW-TOF) Ranging

320-0293 B
November 2011

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This is the fourth in a series of documents that focus on the practical application of Time Domain's Ultra Wideband (UWB) technology, as embodied by the PulsON 400 (P400) Ranging and Communications Module (RCM). These documents are intended to be used as background technical information by system engineers, programmers, and managers interested in determining how UWB can be used to solve real world problems.

Part One: Scratching the Niche
What is the P400 RCM and why is it needed?

Part Two: UWB Definition & Advantages*
What are the advantages of UWB signaling and how do we optimize performance?

Part Three: Two-Way Time-Of-Flight (TW-TOF) Ranging
How does it work?

Part Four: Tracking Architectures Using Two-Way Time-of-Flight (TW-TWOF) Ranging
Which one is right for you?

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*An expanded version of this paper (which discusses radar and other advanced capabilities) is available on the Technology page of the Time Domain website (http://www.timedomain.com/technology.php).

Tracking vs. Navigation

The P400 RCM supports both “Tracking” and “Navigation” systems. “**Tracking**” typically refers to applications where the infrastructure monitors the motion of a person or device, such as tagged items in a warehouse or a scene commander monitoring the location of emergency responders within a burning building.

On the other hand, “**Navigation**” typically applies to systems where the mobile vehicle, sensor, or person has a need to measure and maintain his location relative to a given coordinate system. Commercial GPS units in automobiles or INS/GPS units in military vehicles or munitions are typically seen as navigation devices.

The P400 RCM can support both Tracking and Navigation applications. *As a peer-to-peer precision distance measurement device it is somewhat architecture agnostic*. Typically the type of system, Tracking or Navigation, determines where the computer with “solver” algorithm resides. This computer combines range measurements (and possibly other available location sensors) to produce a position solution. In a Tracking system the solver is usually integrated into a centralized base-station computer. In a Navigation system the solver is typically integrated into the embedded processor on the vehicle, sensor, or hand-held device.

Often military and industrial applications have a need for both Tracking and Navigation in that the autonomous vehicle requires navigation support while the commander also has a need to continuously track vehicles and squad members for situational awareness. Quite often an additional radio system is used to send location information from mobile to commander or vice versa. *The P400 RCM is a RF system with integrated data communications and therefore inherently supports these hybrid tracking/navigation systems*.

Reference and Mobile Nodes

Typical tracking systems consist of “Mobile” and “Reference” devices or “Nodes.” The (x,y,z) coordinates of **Reference Nodes** are known to the localization system and the locations of the **Mobile Nodes** are solved relative to the Reference Nodes. Reference Nodes are often called “Anchors” when they are at well-known, static locations.

The P400 RCM is not by itself a tracking or navigation system. Rather it provides maximum flexibility to a diverse set of localization architectures as a peer-to-peer RF range measurement device with integrated wireless communications (the wireless communications is used to coordinate ranging traffic and propagate reference position data). The RCM is used to measure distance between:

1. Mobile to Mobile (for propagated referencing or cooperative relative behaviors such as formation and following)
2. Mobile to Reference (for precise positioning or drift correction)
3. Reference to Reference (for extra precision during ad-hoc anchor setup)
4. Moving Reference to Mobile Target (for autonomous vehicle safety and situational awareness)

Although Reference Nodes are easily understood when static, in fact any node with an instantaneously accurate dynamic position can be used as a Reference Node. For example, GPS satellites are used as

Reference Nodes but they are not static. Their position is dynamically updated and propagated wirelessly to Mobile GPS receivers which localize based on the received position and time delay between multiple GPS "Anchors."

Likewise, in an RCM-aided localization system any node with instantaneously accurate position can be used as a Reference relative to a neighboring node with less accurately known position. This "**Propagated Reference**" technique can extend the range of the tracking system but at the expense of propagated position error. Typically a temporary static node with good localization must be accessed periodically to limit propagated error.

Therefore in a RCM-enabled dynamic or ad-hoc tracking system the coordinate system is typically based on 1) temporary setup of outdoor GPS-enhanced anchors, 2) a central vehicle with good global localization or, 3) determined as an optimal mix of a system of moving GPS locations augmented by precision ranging and wireless communications.

In any case, *the localization of the Mobile Nodes can never be more accurate than the localization of the Reference Nodes.*

Range Accuracy and Geometric Considerations

The P400 RCM provides peer-to-peer range measurements with accuracies of a few centimeters. Multiple range measures between Mobile and Reference Nodes are combined to produce a position. This solution method is called Trilateration (as opposed to Triangulation when two or more anguluar measurements are combined.) The basic notion is the intersection of circles in a 2D system:

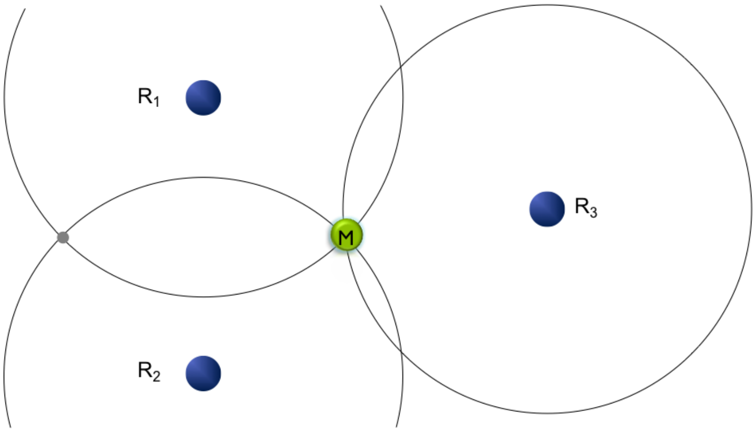

Fig. 1: The distances between Reference Nodes R1, R2, and R3 are combined to produce a location for Mobile Node M

An important consideration for developing Trilateration-based tracking systems is that the RCM range measurement will have error. From the point of view of the **Solver** algorithm, which combines range measurements with Reference coordinates to produce a position estimate, the range measurements are best depicted as intersecting annuli with a Poisson-distributed range error with a standard deviation of 2–10 cm depending on the channel between nodes. This error is fundamentally based on timing jitter and pulse time-of-arrival measurement in the embedded leading edge detection algorithm (see *Part Three: Two-Way Time-of-Flight Ranging* for more information).

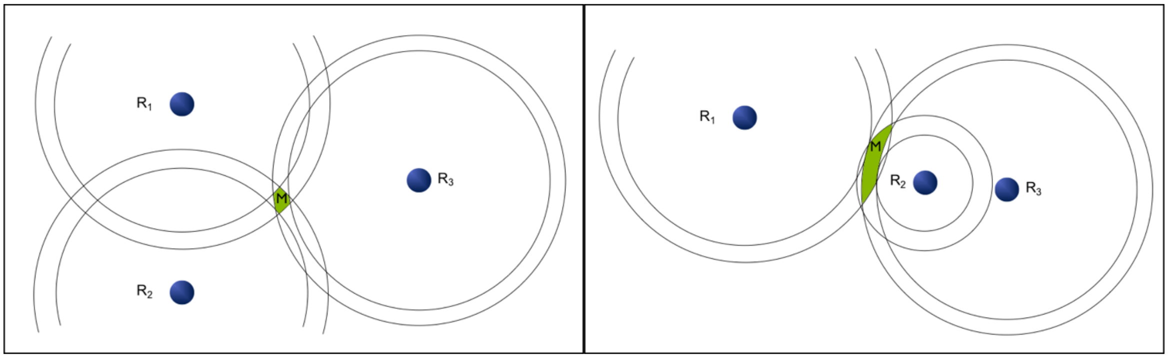

Fig. 2: Two examples with identical range errors (thickness of annuli) resulting in quite different position errors based on the relative geometry of the Reference Nodes

Using this illustration it becomes apparent that the geometry of the Reference Nodes relative to the Mobile Node can have a large effect on the resulting position error. This Geometric Dilution of Precision (GDOP) is common to all Reference-based tracking and navigation systems. GDOP has a large effect when multiple Reference Nodes are mounted on vehicles, with physical limits to possible separation distances. In this case the distance from vehicle to target will be very accurate, but the cross-range dimension will suffer as the distance between Reference and Mobile increases.

Using other vehicles or persons can increase the dynamic baseline separation and provide improved results. In advanced navigation systems with distributed solvers the Mobile Node itself instantaneously decides the "best" References for range query based on their relative geometry. In these systems an active database of nearby nodes positions must be maintained by the Mobile processor.

Three Types of Solvers

The **Solver** algorithm can reside in either a single base station computer (centralized architecture) or inside each Mobile Node (a distributed architecture). *In any event, the Solver must take into account that the circles won't intersect at only one spot*. For example, three Reference ranges can intersect at 6 distinct locations (2 for each Reference/range circle).

Three typical approaches to Solvers include 1) a **Linearized Least-Squares** Solver, 2) a **Geometric** Solver**,** or 3) an **Optimal Recursive Estimator** Solver.

The typical **Linearized Least-Squares Solver** uses a Gauss-Newton approach to iteratively minimize the error in a system of equations based on the Euclidean distance between the common Mobile coordinates and each of the Reference coordinates. This approach has the advantage that N Reference/range measures can be used. But it has the disadvantages that a) it is iterative and therefore can have varying computation times, b) it is nonlinear such that there are conditions in which very incorrect solutions could result, and c) a position seed is needed to start the iteration. The closer this seed is to the true position the faster the algorithm will converge. Typically this seed is the coordinate position solved during the previous measurement.

<u>One final note</u>: this algorithm also requires grouping of 3 or more near-simultaneous range measurements to multiple Reference Nodes. This requires sufficient coverage and update rate for all the Mobiles being tracked.

The typical **Geometric Solver** finds the point intersections of all the circles, clusters these points to throw out outlying intersections found at secondary intersections, and calculates the Mobile position estimate as the centroid of these primary cluster. In the figure below the secondary intersections are depicted in orange while primary are in green. The centroid of the shape outlined by the primary (green) points comprises the resulting solution.

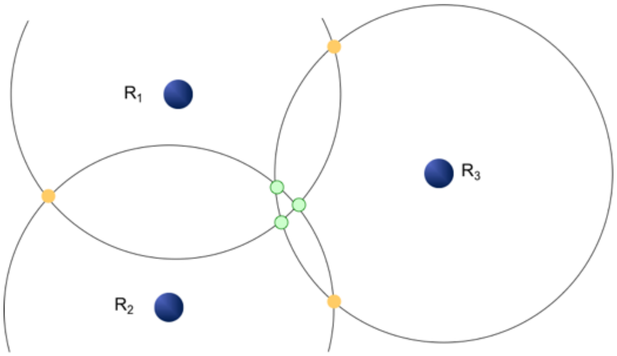

Fig. 3: Geometric intersection and clustering

The Geometric Solver has the advantage that a seed is not required. It also, in certain conditions, can produce the most accurate solution of all the approaches. It has the disadvantage of requiring a clustering/association algorithm that typically requires computation on the order of 2*N where N is the number of references. Often the Geometric Solver is used to initialize the seed of Least-Squares or Optimal Filter based systems.

Finally, the **Optimal Recursive Estimator Solver**, typically a derivation of the standard Kalman Filter, can be used. This technique combines a simple model target motion with range measurements and Reference locations to produce a solution that is optimal in the sense that acceleration error and range errors are properly mixed based on observations and model estimates. An Extended Kalman Filter is necessary due to the non-linear nature of Euclidean distance formula. In most cases the nonlinearity of the system is not severe enough to warrant an Unscented Kalman Filter approach unless maximum accuracy is required. Particle filtering may be used when ample sampling time is available, such as in the case of indoor, through-wall survey.

There are a number of advantages to the Optimal Filter solver technique including a) its recursive nature makes use of the previous solution, thus implicitly removing occasional outlying range errors, b) it allows individual range measurements to be folded into the solution as they are measured, no grouping and

Trilateration are required, c) the solution estimate is updated by the motion model when range measurements are not available, thus extending the area of coverage or requiring fewer Reference nodes, and d) other localization sensors, such as GPS, INS, barometric pressure, odometry, and/or video analytics can be optimally combined with UWB ranging to provide a final navigation solution which is robust against errors and dropouts of any individual modality.

Drawbacks of Optimal Filters are that they can be complex and difficult to optimize, typically requiring long test/rework cycles. In addition, the motion model must be fairly accurate for good results. Humans tend to walk without apparent inertia so care must be taken to de-emphasize simple model predictions through large acceleration error values.

Centralized Tracking System Architecture

An example of a Centralized Architecture is shown in **Figure 4**. In this configuration, four RCMs are defined as Reference Nodes (named A1, A2, etc) and their (x,y) locations relative to each other define the coordinate system. These Reference Nodes could be mounted on the corners of a vehicle or mounted on poles in fixed locations. The References are in turn connected to a central processor that hosts the Solver. The Solver has been programmed with the location coordinates of each Reference Node and sequentially polls each Reference Node commanding them to issue a range request to RCM Mobile unit Ma. Note RCMs each contain two individually selectable antenna ports, enabling 4 Reference points using only two RCM devices.

Figure 4 shows a ranging conversation between Reference A1 and Mobile Ma producing range measurement R1-A which is subsequently reported to the Solver. This conversation is repeated in a round-robin fashion around the vehicle. After an initial startup time the Solver can produce an updated position estimate each time it receives a new range measurement. *The resulting update period is once per range conversation.*

Although having different purposes this Tracking architecture is topologically identical to many “Reader” nodes tracking assets in a warehouse. It is easily expandable to multiple Mobile Nodes and has the advantage that it does not require a data network.

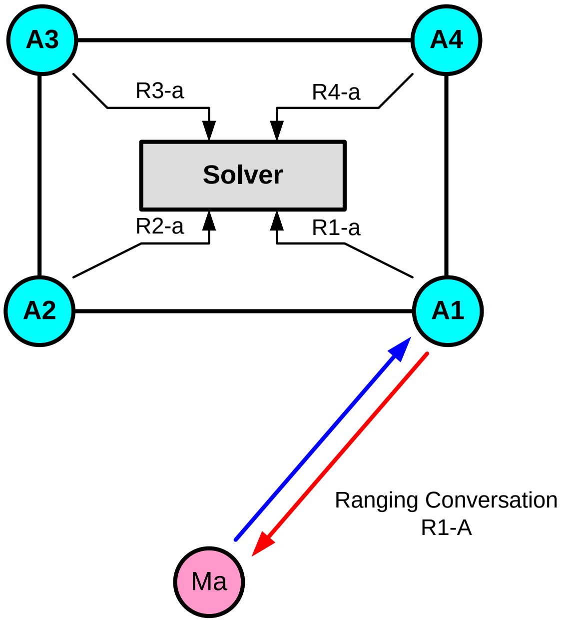

Fig. 4: Diagram of a centralized tracking architecture

Note that if both the Anchors/Solver and Mobiles units are moving relative to each, then the polling must be fast enough such that the error introduced by the movement of the devices over time is insignificant.

If more than one Mobile is operating in the area, then the Solver needs to poll each Mobile in sequence. If the Reference system is a vehicle it could autonomously follow a specific Mobile while maintaining a safe distance from other Mobiles.

Distributed Navigation Architecture

In the simplest version of a distributed architecture the Reference RCMs are placed in fixed, known locations (Anchors) and a Solver algorithm runs on a computer inside each Mobile Node. The Solver commands the Mobile RCM to sequentially issue range measurements to each of the Reference Nodes. Based on its knowledge of the Reference (x,y) locations and the associated range measurements, the Solver computes its own position.

Given a mechanism for sharing airtime, multiple Mobiles with their own solvers take turns ranging to the Anchors. The RCM peer-to-peer ranging allows Mobiles to also range to other Mobiles to extend the navigation system further inside a building or other GPS-denied areas (“propagated reference”.)

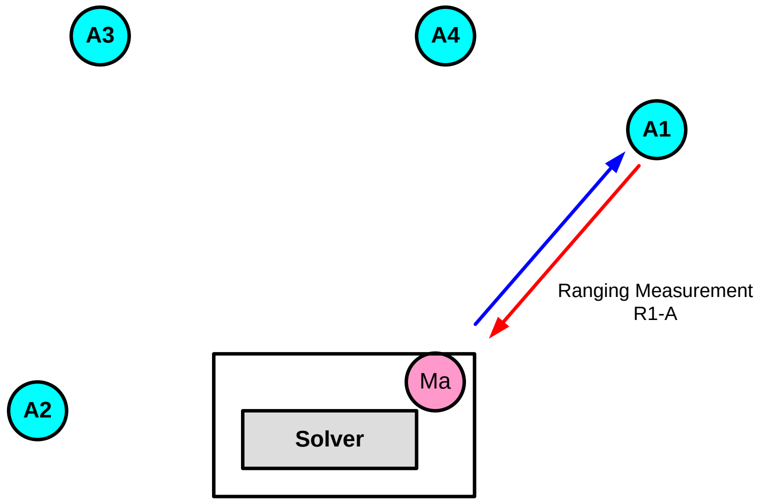

Fig. 5: Diagram of a distributed navigation architecture

Case Study 1 – "Follow Me" (Centralized Architecture)

Figure 6 illustrates a "Follow Me" application. The goal of this application it insure that an unmanned, cargo laden vehicle follows a leader at a predetermined distance while avoiding other team members. The photo on the left shows the leader vehicle configuration. The vehicle has been equipped with four ranging radios (small white circles) mounted on the corners of the vehicle as Anchor Nodes, while the Leader has a ranging radio mounted on his hip (small white circle) as a Mobile. The location of the vehicle relative to the leader is determined by ranging from the leader radio to each of the vehicle radios. By knowing theses ranges and the location of the ranging radios on the vehicle the Solver on the vehicle computes the location and heading of the leader relative to the vehicle such that the vehicle can follow and maintain a safe distance.

Similarly, each of the non-leader team members is also equipped as a Mobile with a ranging radio. The white circles in the right hand photo indicate location of the non-leader radios. Through a similar localization computation process, the vehicle can determine the location of each of the team members and automatically keep a safe distance or automatically halt when they advance.

Fig. 6: Example of "Follow Me" application

Case Study 2 – First Responder (Centralized Architecture with Range Extension)

In this case study firefighters arrive and enter a burning building. The position of these firefighters must be maintained at a base station outside the building. If the firefighters become trapped, lost or injured, then knowledge of their position will allow the scene commander to give precise directions to a Rapid Intervention Team (RIT.)

Figure 7 shows typical data taken as a person enters a building. While this data shows the track on only single individual, this scenario was tested with up to 10 firefighters simultaneously entering and operating in the building.

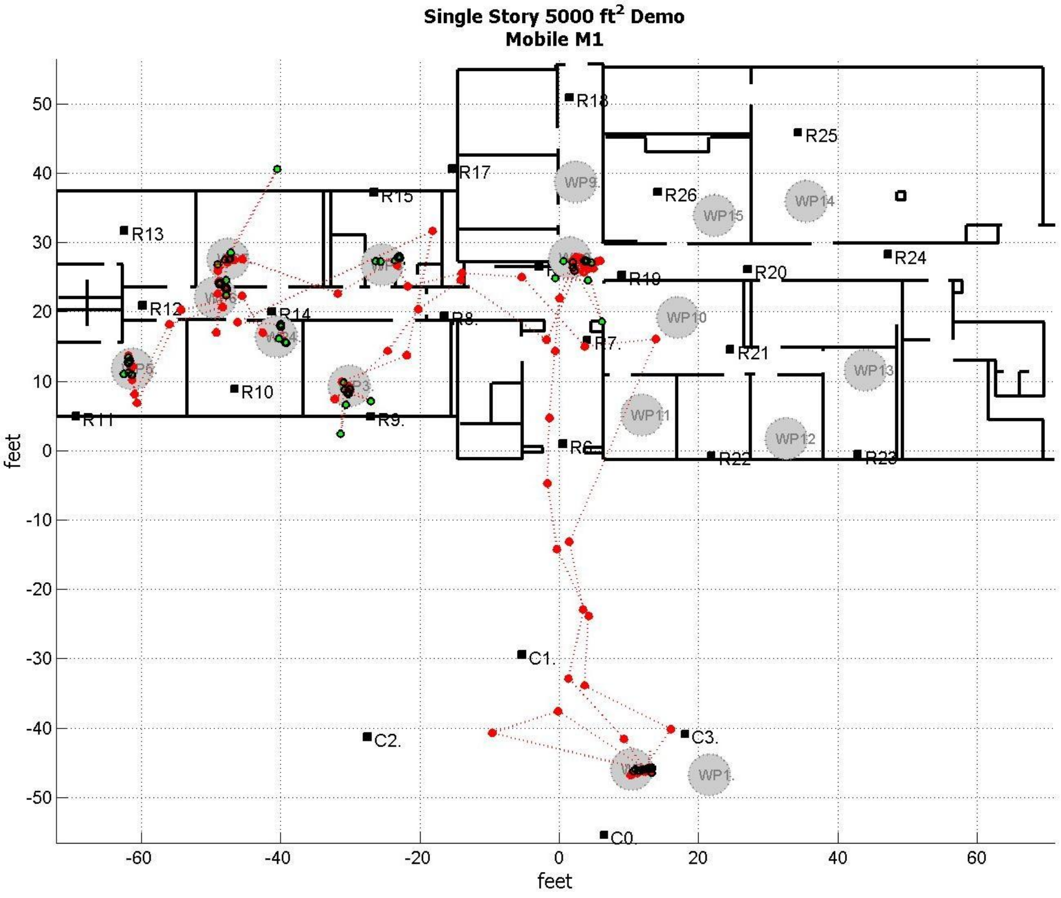

Fig. 7: Example of First Responder application

As the firefighters arrive on scene they first install a network of reference Anchors (C0 through C3). Any personnel entering the building will be located by the Anchors and tracked as they approach and enter the building. The red dots indicate the recorded path that one firefighter took. In this test, the firefighter was instructed to proceed to a number of the gray waypoints and wait at each for a few moments. By comparing the location of the red dots to the gray waypoints one can quantify the accuracy of the system at locating personnel inside the building. In this case, the achieved accuracy was approximately +/-1 meter.

This experiment was implemented with UWB only and no aiding sensors. Each position required access to four Reference Nodes. When the firefighter approached the limit to the area covered by Reference Nodes the system would instruct him to drop an additional Propagated Reference Nodes (aka breadcrumbs). In this way it was possible to extend the coverage to an area well beyond the operational range of the first 4 Anchor nodes.

One of the lessons learned from this experiment is that distributed personnel tracking systems could greatly benefit from multiple location technologies. By configuring the fire fighters equipment with a ranging radio, IMU and GPS, it would be possible to use the best features of each to increase both the accuracy of the location measurement as well as the robustness of the system. Utilizing these synergistic localization technologies also points towards implementation of a distributed optimal estimator technique. This technique inherently allows a more sparse array of Anchor nodes with wider separation and elimination of the breadcrumbs.

In fact, by incorporating GPS with UWB, one could consider this example to be effort at projecting GPS localization and timing into a building. Furthermore GPS with UWB augmentation would excel at precision localization of the outdoor Anchor positions. The accuracy and geometry of these outdoor Anchors are crucial for successful ad-hoc tracking inside a building.

Case Study 3 – Distributed Sensors (Distributed Architecture)

The goal of this effort was to search a warehouse for signs of radioactivity and produce a geolocated sensor "heat map" of the facility. Typical inexpensive radiation detectors are omni directional. As the detector moved through the warehouse its timetagged and geotagged sensor measurement was recorded.

In this demonstration six UWB ranging radios were distributed through the warehouse and used as Anchors. The mobile radiation sensor hosted the solver algorithm as well as a UWB ranging radio. A single sensor was manually moved through the building, but the system could easily be expanded to support multiple mobile sensors and autonomous vehicles.

As the sensor maneuvered through the warehouse, radiation readings were measured and recorded along with geotag and timetags. The post-processed result is provided in **Figure 8**. On the left is a blueprint of the warehouse, with the Anchors marked in red and the path of the Mobile marked in green. On the right side is the radiation heat map produced by the system.

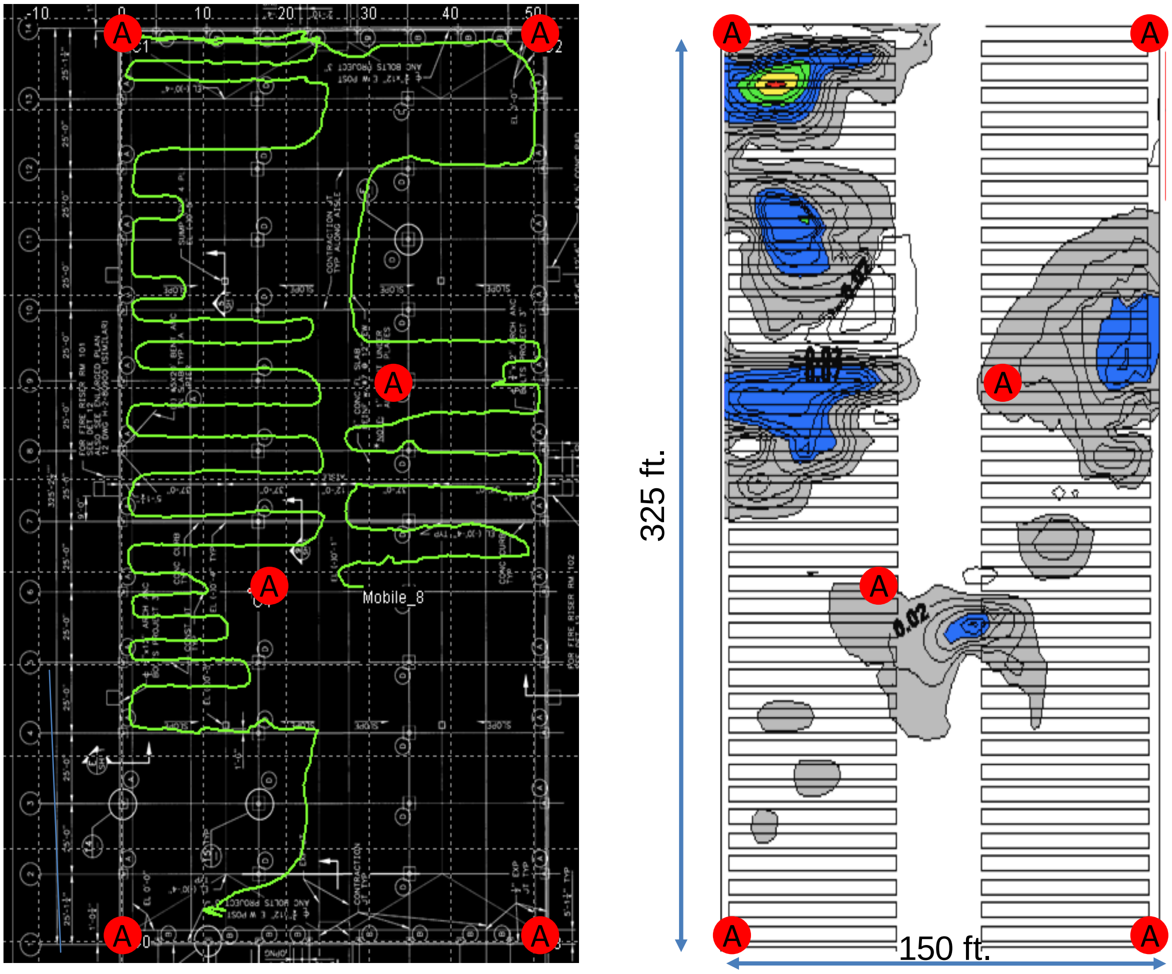

Fig. 8: Distributed architecture using radiation sensor and UWB ranging radio tracking system to produce a trail history (at left) and a radioactivity heat map (at right)