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# Time Difference Localization for Assembly Bay Hand Tool Tracking

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## Abstract

This disclosure describes a system for real-time localization of hand tools within an industrial assembly environment. The system utilizes time difference of arrival (TDOA) principles from fixed reference tags to pinpoint the spatial coordinates of tool-mounted transponders. This arrangement addresses the problem of inadvertently using a specific tool at an incorrect assembly station, a common error that can lead to manufacturing defects which are often discovered only much later in the production process, incurring significant rework costs and production delays. The disclosed system provides continuous positional data to prevent such misapplications.

## 1. Technical Field

[0001] The present disclosure relates to real-time asset tracking and localization systems, particularly for industrial environments suchasting assembly bays. More specifically, it concerns the use of time difference of arrival (TDOA) techniques to precisely determine the position of moving objects, such as hand tools, within a defined workspace.

## 2. Technical Context

[0002] In complex manufacturing and assembly operations, hand tools are frequently used at various stations along a production line. The specific type of tool required often varies between adjacent stations, or even for different operations at the same station on different product variants. A common source of manufacturing defects arises when a tool intended for one operation or station is mistakenly used at another. Such errors, if not immediately detected, can lead to incorrectly assembled components, requiring extensive rework or even scrap later in the production process, after the vehicle or assembly object has progressed significantly down the line. The detection of such defects can be costly and time-consuming, necessitating systems that can prevent their occurrence in real time. Traditional methods of tool control, such as tool crib check-out systems or visual inspection, are often insufficient to prevent these real-time misapplications.

## 3. System Overview

[0003] The system provides real-time, three-dimensional localization of hand tools within a defined assembly bay. It operates by affixing a compact tool transponder (10) to each hand tool requiring tracking. This tool transponder (10) periodically emits short radio frequency (RF) pulses. A network of fixed anchor nodes (12) is strategically deployed within the assembly bay. Each anchor node (12) receives these RF pulses and records the precise time of arrival. These time-of-arrival (TOA) measurements are then transmitted via a communication network (14) to a central processing unit (16). The central processing unit (16) calculates the differences in the arrival times of the RF pulses at multiple anchor nodes (12) to determine the tool transponder's (10) position using TDOA algorithms. The calculated position can then be displayed on a display unit (18) or integrated into a higher-level control system to provide alerts if a tool is detected in an incorrect location for its intended use. FIG. 1 illustrates the overall system architecture and data flow.

## 4. Components

[0004] The system comprises several key components:

[0005]

- **Tool Transponder (10):** A small, battery-powered device designed to be attached to a hand tool. It contains a radio frequency (RF) transmitter capable of emitting short, precisely timed pulses, typically in the ultra-wideband (UWB) spectrum. The pulse repetition rate can be configured, for example, from 1 to 10 Hz, balancing update rate with battery life. The power output is sized to ensure a reliable signal across the intended operational range, typically 5 to 50 meters, while complying with regulatory limits. An internal clock maintains timing accuracy for pulse generation.

[0006]

- **Anchor Nodes (12):** These are stationary RF transceivers mounted at known, fixed locations within the assembly bay. Each anchor node (12) is equipped with a highly stable internal clock, synchronized with other anchor nodes (12), to accurately record the time of arrival of pulses from the tool transponder (10). A minimum of three anchor nodes (12) are required for two-dimensional localization, and a minimum of four for three-dimensional localization. These nodes communicate their received TOA data to the central processing unit (16) via the communication network (14). They typically feature omnidirectional or sectorized antennas depending on the desired coverage pattern and potential interference sources.

[0007]

- **Communication Network (14):** This network facilitates data transfer between the anchor nodes (12) and the central processing unit (16). It can be implemented using wired Ethernet, industrial wireless protocols such as Wi-Fi or proprietary mesh networks, or a combination thereof. The network is designed to ensure low latency and high reliability for time-sensitive TOA data.

[0008]

- **Central Processing Unit (16):** This unit receives the TOA data from all participating anchor nodes (12). It executes the TDOA localization algorithms to compute the real-time position of each tool transponder (10). The TDOA algorithm calculates hyperbolic surfaces based on the time differences, and the intersection of these surfaces yields the tool's coordinates. The central processing unit (16) also manages the synchronization of the anchor nodes (12) and can store historical positional data. It can interface with external systems for tool assignment and zone definitions.

[0009]

- **Display Unit (18):** A human-machine interface (HMI) or monitor that presents the real-time location of tools graphically. It can overlay tool positions onto a map of the assembly bay, highlighting specific work zones. It is configured to provide visual or audible alerts when a tool is detected outside its assigned work zone or in an incorrect zone for a specific operation.

[0010]

- **Assembly Vehicle (20):** The primary object being assembled, such as a vehicle chassis or large component, which moves through the assembly bay. This object can potentially obstruct the line of sight between a tool transponder (10) and one or more anchor nodes (12), an effect known as shadowing.

## 5. Operation

[0011] The system's operation proceeds through initialization, steady-state tracking, and fault handling:

[0012] **Initialization:** Upon system power-up, or when a new tool transponder (10) is introduced, the anchor nodes (12) undergo a synchronization process. This involves exchanging timing signals to establish a common time base with a precision on the order of picoseconds, crucial for accurate TDOA calculations. Each tool transponder (10) is associated with a specific tool type and its allowed operational zones within the central processing unit (16). The known coordinates of each anchor node (12) are pre-loaded into the central processing unit (16).

[0013] **Steady-State Tracking:** During normal operation, each tool transponder (10) periodically emits an RF pulse, for example, every 100 to 500 milliseconds. These pulses propagate through the assembly bay. Multiple anchor nodes (12) receive these pulses. Upon reception, each anchor node (12) precisely timestamps the arrival time of the pulse using its synchronized internal clock. The anchor nodes (12) then transmit their unique identifier and the recorded TOA measurement to the central processing unit (16) via the communication network (14). The central processing unit (16) collects these multiple TOA measurements for a single pulse event. It then calculates the differences in arrival times between pairs of anchor nodes (12) to generate a set of TDOA values. These TDOA values, combined with the known anchor node (12) positions, are fed into a multilateration algorithm to compute the 3D coordinates (X, Y, Z) of the tool transponder (10). This positional data is updated continuously, enabling real-time tracking. The computed position is then compared against predefined operational zones for the specific tool type. If the tool transponder (10) is detected within an incorrect zone, an alert is generated on the display unit (18).

[0014] **Fault Handling and Shadowing:** In situations where a tool transponder (10) is shadowed by an assembly vehicle (20) or other large metallic structures, the direct line-of-sight path to one or more anchor nodes (12) may be obstructed. This can lead to non-line-of-sight (NLOS) signal reception, where the signal travels via reflections, resulting in delayed and potentially erroneous TOA measurements. The system is designed to mitigate this. If fewer than the minimum required anchor nodes (12) receive a direct signal, or if received signals exhibit characteristics indicative of NLOS (e.g., significantly delayed arrival times inconsistent with other measurements), the central processing unit (16) employs filtering techniques. This may involve statistical outlier rejection, weighting measurements based on signal quality, or temporarily reducing the update rate until a clearer signal path is reestablished. In cases of complete signal loss from the required number of anchors, the system can report the last known position and indicate a "lost signal" status. The anchor arrangement shown in FIG. 2, with anchor nodes (12) positioned at elevated points, aims to minimize shadowing effects by providing multiple potential line-of-sight paths.

## 6. Example Embodiments

[0015] **Embodiment 1** This embodiment utilizes a distributed array of at least four anchor nodes (12) mounted at a height of approximately 3 to 5 meters along the perimeter of a rectangular assembly bay. The anchor nodes (12) communicate with the central processing unit (16) via a dedicated wired Ethernet network, ensuring minimal latency and high data integrity. Tool transponders (10) emit UWB pulses at a rate of 5 Hz, providing a positional update every 200 milliseconds. The central processing unit (16) employs a non-linear least squares algorithm for TDOA calculation, achieving a positional accuracy of approximately 10 to 30 centimeters in X and Y, and 20 to 50 centimeters in Z. This accuracy is sufficient to distinguish between adjacent work stations spaced 1 to 2 meters apart, as shown in FIG. 3 where stations (22, 24, 26) are distinct zones.

[0016] **Embodiment 2** In this configuration, a denser array of anchor nodes (12) is deployed, with nodes positioned at closer intervals, such as every 5 to 8 meters, both along the perimeter and potentially within the assembly bay, mounted at varying heights between 2 and 6 meters. The anchor nodes (12) communicate wirelessly via a robust industrial Wi-Fi network, leveraging time synchronization protocols such as Precision Time Protocol (PTP) for clock alignment. Tool transponders (10) operate at a lower pulse repetition rate of 2 Hz to conserve battery life, providing updates every 500 milliseconds. The central processing unit (16) incorporates a Kalman filter to smooth positional estimates and predict tool movement, enhancing tracking continuity even during brief periods of signal degradation or shadowing. This setup is designed to achieve a higher positional accuracy, typically 5 to 15 centimeters in X and Y, which allows for distinguishing smaller, more densely packed work areas, perhaps with separation distances down to 0.5 meters.

[0017] **Embodiment 3** This embodiment focuses on enhanced resilience to shadowing. A redundant array of anchor nodes (12) is used, with at least six nodes per assembly station area, including nodes mounted overhead and at lower levels. For example, two nodes at 4 meters height, two at 2.5 meters height, and two at 1 meter height, distributed around the work cell. Communication is via a proprietary UWB mesh network where anchor nodes (12) can also relay signals from tool transponders (10) to extend coverage and provide alternative signal paths. Tool transponders (10) are capable of increasing their pulse repetition rate to 10 Hz when a potential shadowing event is detected (e.g., based on signal strength drop or increased multipath indications). The central processing unit (16) utilizes an advanced NLOS mitigation algorithm that dynamically weights or discards measurements suspected of being reflected signals, potentially employing historical data or environmental mapping to improve accuracy. This configuration aims to maintain positional accuracy of 15 to 25 centimeters even when significant portions of the assembly vehicle (20) obstruct direct lines of sight.

## 7. Alternative Configurations

[0018] Instead of UWB, other RF technologies such as Chirp Spread Spectrum (CSS) or narrow-band techniques with phase-based ranging could be used for the tool transponder (10) and anchor nodes (12). CSS offers good ranging performance and multipath immunity, while phase-based ranging can provide high precision over shorter distances. The communication network (14) could alternatively leverage a dedicated fiber optic network for maximum bandwidth and noise immunity, particularly in electromagnetically noisy industrial environments. The display unit (18) could be integrated directly into a tool caddy or workstation, providing immediate feedback to the operator. For very large assembly bays, multiple central processing units (16) could be deployed, each responsible for a specific zone, with a higher-level system aggregating data for overall bay management. Instead of fixed anchor nodes (12), some nodes could be semi-mobile, allowing for re-configuration of work zones if the assembly line layout changes, provided their positions are accurately re-surveyed.

## 8. Parameter Variations

| Parameter | Range | Effect of increasing value | Effect of decreasing value |
|---|---|---|---|
| **Number of Anchor Nodes (12)** | 4 to 12 per 100 m² | Enhanced accuracy, improved NLOS resilience, increased system cost and complexity. | Reduced accuracy, higher susceptibility to shadowing, lower system cost and complexity. |
| **Tool Transponder (10) Pulse Rate** | 1 to 10 Hz | Faster positional updates, shorter battery life, increased network traffic. | Slower positional updates, longer battery life, reduced real-time responsiveness. |
| **Anchor Node (12) Height** | 2 to 6 meters above floor | Improved line-of-sight over obstacles (e.g., assembly vehicle 20), potential for wider coverage. | Increased likelihood of shadowing, reduced coverage, more reflections from floor. |
| **RF Bandwidth** | 500 MHz to 2 GHz (UWB) | Higher ranging precision, better multipath resolution, more complex transceiver design. | Lower ranging precision, worse multipath resolution, simpler transceiver design. |
| **TDOA Algorithm Complexity** | Simple (least squares) to Complex (Kalman filter with NLOS mitigation) | Improved accuracy and robustness, higher computational load on central processing unit (16). | Faster processing, lower accuracy, higher susceptibility to environmental noise and shadowing. |
| **Required Positional Accuracy** | 5 to 50 cm | Requires denser anchor placement, higher pulse rates, more complex algorithms, higher cost. | Allows for sparser anchor placement, lower pulse rates, simpler algorithms, lower cost. |
| **Station Separation (FIG. 3)** | 0.5 to 5 meters | Easier to distinguish stations with lower accuracy systems. | Requires higher positional accuracy to reliably distinguish tools at adjacent stations. |

## 9. Additional Implementations

[0020] The disclosed localization system can be extended to track other assets within the assembly bay, such as automated guided vehicles (AGVs), material handling equipment, or portable test fixtures, by equipping them with appropriate transponders. Integration with an enterprise resource planning (ERP) system or manufacturing execution system (MES) could enable automatic update of work progress or quality control records based on tool usage at specific stations. The system could also be used to enforce safety zones, alerting operators if a tool or person (equipped with a transponder) enters a restricted area. Furthermore, by analyzing historical positional data, efficiency improvements can be identified, such as optimizing tool placement or workflow paths. The Z-axis (height) information can be used to distinguish between tools used on the upper or lower parts of a large assembly, or to verify if a tool has been picked up from a workbench. Positional data can also be used for geofencing tools to ensure they remain within a specific work cell or bay, preventing unauthorized removal or loss.

## 10. Figures

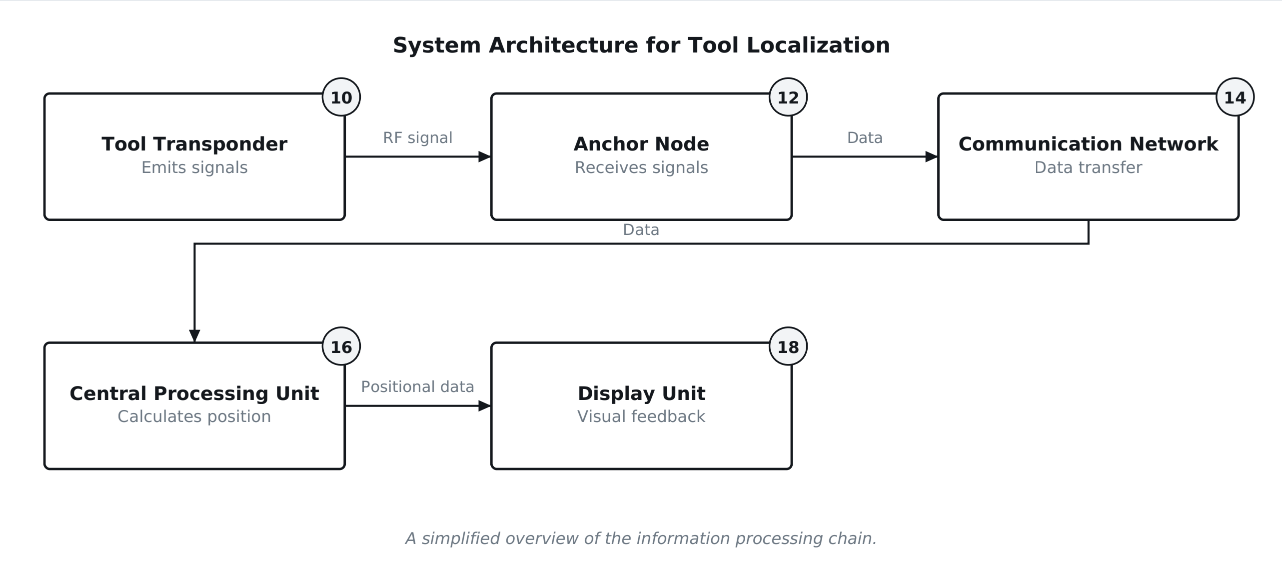


**FIG. 1** This diagram illustrates the primary components and data flow within the real-time tool localization system. PNG

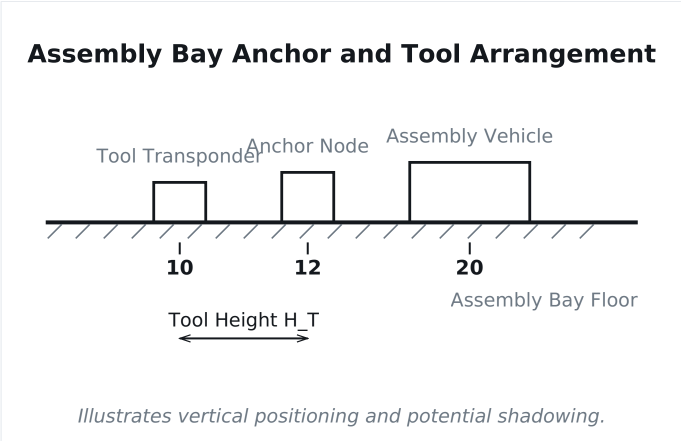


**FIG. 2** This elevation view depicts the placement of anchor nodes relative to an assembly bay and a tool transponder. PNG

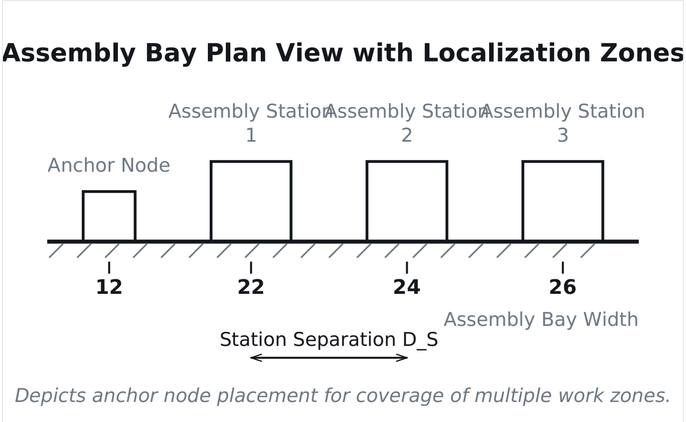


**FIG. 3** This plan view shows multiple assembly stations and the desired localization accuracy zones within an industrial bay. PNG

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