Final Report for the Alpha Foundation for the Improvement of Mine Safety and Health, AFC518

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1. Executive Summary

The purpose of this project is to design a real-time-position guided autonomous vehicle for use in the underground mining environment, aiming to improve health and safety. Existing positioning technologies such as radio-frequency identification (RFID), received signal strength indication (RSSI), inertial sensors, and time-of-arrival (TOA) either provide a low-level of accuracy, necessitate excessive computational power, or require significant infrastructural support respectively. On the other hand, the improved time-difference-of-arrival (TDOA) method developed over the PI's 15 years of indoor positioning research, which poses significant improvements over traditional TDOA schemes, provides decimeter-level accuracy, much lower deployment complexity than existing TOA and TDOA systems and can be implemented without large-scale infrastructural changes. The technology developed over the course of this project is incorporated into a rover-style robotic vehicle and enables autonomous navigation. Implementation of this system greatly reduces the frequency in which human interaction is required in hazardous mining environments and has the potential to automate tasks normally performed by workers operating in areas with high levels of coal dust, noise, or chemical hazards.

One of the priorities for this proof-of-concept (POC) has been to design components with a focus on modularity and expandability.

First, the anchors have been designed to remove the requirement for time synchronization among separate anchors. In existing time-based technologies, time synchronization among the anchors is best achieved by connecting all anchors to a common clock source, for example, via optical fiber cables. The time-synchronization-free feature of this POC greatly increases the system's scalability, since it allows anchors to be flexibly added/removed, to increase the positioning accuracy at any particular area or to expand the coverage area of the network.

Second, the anchors could communicate with the centralized server wirelessly, removing the need for running cables throughout the mine. The RF tags have also been designed to be modular. They can be installed on a wide variety of vehicle platforms. A centralized server is used to process the raw data from the anchors, compute the vehicle's position and calculate a trajectory. In this manner, there is no need for the vehicle to be equipped with an expensive high-powered data processor. The trajectory algorithm uses the vehicle's position, orientation and destination to calculate a sequence of coordinates between the vehicle and the destination. Directional commands are then sent to the vehicle as it traverses the trajectory.

An evaluation of the positioning system can be conducted by two tests: one is tracking the mean deviation between the RF tag's true position and the tag's estimated position, and second is tracking the mean deviation between the tag's known trajectory and the tag's estimated trajectory. The mean deviation from a stationary reference point has been found to be between 0.3-1 meters from the true position and thus is successfully estimating its location. The mean deviation from a known trajectory has been found to be within 1 meter when the vehicle is moving under 1 meter per second. Both the stationary and moving tests have successfully reported the vehicle's location to be within the expected values. The trajectory algorithm is under continuing development. Presently, the vehicle is able to move autonomously over short distances successfully without user input.

The technology readiness of this proof-of-concept is on-track towards developing a working prototype. Several improvements can be completed before prototype implementation. The TDOA algorithm can be further improved by moving several key functions from Matlab to C++ or Python, to increase the number of position estimates per second thus reducing the error between reported position and true position. The anchor antenna radiation pattern can be optimized specifically for the unique underground mine environments. An Inertial Measurement Unit (IMU) has been a supplementary focus of the proof-of-concept and can be added to a working prototype to improve positioning accuracy in mining conditions where strong signal strength is difficult to achieve, or a higher level of accuracy is required. A blending algorithm can be added to the server to combine TDOA and IMU position reports. The trajectory algorithm development can be completed and improved to provide obstacle avoidance and "best route" determination. The Graphical User Interface (GUI) can be improved by adding features such as a live video stream from the vehicle and actual trajectory versus calculated trajectory visualization. Finally, the vehicle platform by reducing the wheel deflection during turns, increasing the payload capacity and increasing traction.

2. Concept Formulation and Mission Statement

Underground machinery such as Load-Haul-Dump (LHD) vehicles are prevalent in the mining industry. These vehicles improve safety, productivity and help automate repetitive and tedious underground mining tasks. While the demand for autonomous vehicles in underground mines is well documented, accurate and real-time positioning is still lacking. Providing a continuous accurate position is one of the most important pieces of the autonomous vehicle puzzle. Most above-ground autonomous vehicles require the global navigation satellite system (GNSS) such as GPS or GLONASS to obtain the position. Positioning in underground mine environments is a challenging problem from a technical standpoint [1-4]. Underground mines have numerous obstacles and reflectors that prevent clean propagation of electromagnetic waves [5]. It is impossible, for instance, to receive satellite signals underground. As a result, even more involved technologies such as high sensitivity GNSS [6] cannot be used in such environments.

2.1. Concept Formulation

Indoor and below-ground environments require distinctive sets of technologies for positioning. Common approaches include using radio frequency signal, received signal strength indicator, inertial sensors, sound or light, and image or video. While no technology dominates in the underground mine application, each of the them has their own advantages and disadvantages [7].

RFID is a common tracking technique using RF signal proximity for underground tracking applications [8]. The position of the target count on reading encoded identifier from each installed tag [9]. Thus, the RFID system is mainly used for presence detection rather than real-time positioning. The RSSI method builds on either RF beacons or magnetic anomalies and requires a tedious and expensive "fingerprinting" step, which creates a database of RSS-to-position or magnetism-to-position pairs [10-11]. Any change of the mine structure, even the changed presence of people, could require re-calibration of the fingerprinting database. This disadvantage makes the RSSI method expensive and impractical for underground mines. Inertial sensors include accelerometer, gyroscope, and digital compass, can be used as an indoor positioning solution to determine the target position and movement. This method suffers from compounded error. As a standalone system, the error accumulates over time and distance and worsens the accuracy, thus is unreliable for underground mines. However, it is possible to combine the sensor measurement with other positioning methods. The time-based RF positioning system utilizes the fact that the speed of radio waves is finite and known to accurately position objects. A time-based method is implemented in [12] to achieve sub-meter accuracies in underground mines. Unlike RSS-based methods, the accuracy depends on the bandwidth of the transmitted radio signals. Transmitters with higher bandwidth signal can be positioned with greater accuracy [13]. Time-based methods are the most accurate yet practical method for positioning objects in most environments.

Most time-based positioning systems use one of the two following methods: TOA and TDOA. TOA is the technique based on measuring the time the target sends the signal and the time the signal arrives at the anchor placed at a given reference point. Then, the distance from the reference point can be calculated by multiplying the time difference with the speed of light. Due to this timing coordination requirement, TOA system requires anchors to be in constant communication with all target units being localized. This causes significant slowdown when operating with a large number of tags [14]. On the other hand, TDOA relies on the difference between the times a transmitted signal reaches two separate anchors. Direct target-to-anchor distance is not needed in a TDOA system. Instead, the relative received signal time delay is used to make a position estimate by providing anchor-to-anchor synchronization. This effectively forms a hyperboloid-shaped locus of possible positions around the two anchors. By evaluating many receiver pairs, multiple hyperboloids can be formed, all of which will intersect at the target's position. TDOA systems have much simpler tags and are capable of higher update rates compared to TOA systems that are difficult to deploy due to the synchronization requirement. TDOA systems show the most promise for autonomous vehicles and inventory tracking in underground mines [15].

2.2. Mission Statement

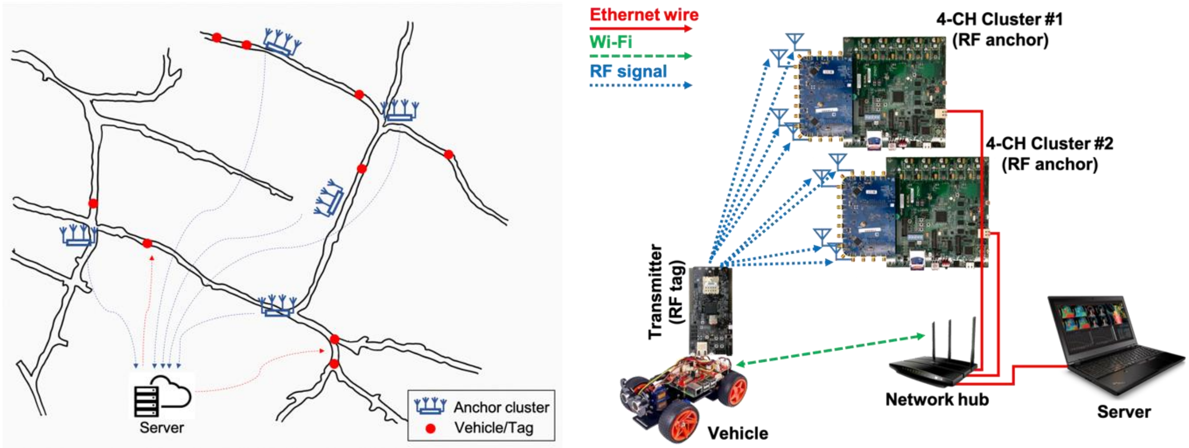
The goal of this project is to complete a proof-of-concept of the TDOA-based RF system that provides real-time position estimation of the robotic vehicle. The vehicle is either manually or autonomously controlled by the back-end server to maneuver to the destination. The core algorithms ran on the server provides the results from converging TDOA position estimations and plans the vehicle's moving path. Specifically, the user can specify any destination on the map. The vehicle will be guided by the position system to travel along the path or stop at the point selected by the user.

3. Proof-of-concept Technology Components

3.1. System Design and Architecture

The system developed in this project implements an improved TDOA method that will achieve decimeter-level positioning accuracy in an underground mine as illustrated in Figure 1. The system consists of four major parts: (a) a centralized localization server hosting the core algorithms, (b) a robotic vehicle controlled by the backend server, (c) two anchors, each with four receive antennas, and (d) multiple tags that are attached to the vehicle and transmit positioning signals. Note that one tag is sufficient to position a vehicle, but multiple tags on the same vehicle will improve the accuracy of the vehicle's position estimates. Also, multiple tags placed at different parts of the vehicle can be used to estimate the vehicle's moving direction.

Throughout the past 15 years, the PI has successfully delivered numerous indoor positioning systems [16-38] to a variety of different sponsors, including centimeter-accurate location for aircraft manufacturing automation, radio positioning measurement for construction, worker positioning in construction sites, and elderly activity tracking for healthy aging. The architecture and algorithm required to successfully deploy a similar positioning system for underground mine applications is very mature.



(a) (b)

Figure 1: (a) Proposed network architecture in underground mine. (b) System inter connections with actual components.

The core of this architecture is a TDOA estimator that contains significant improvements. In traditional TDOA schemes, a minimum of three anchors (per area) is required for two-dimensional positioning. All the anchors distributed in space must be time-synchronized to a precision of picoseconds to achieve sub-meter positioning accuracies. Synchronizing the anchors creates a significant infrastructural challenge for underground mines.

A unique feature of the proposed technology is that time synchronization of the anchors distributed in the mine is not required, making the network easy to deploy and to maintain. As illustrated in Figure 1(a), each anchor has four antennas. The signals of each tag are received by at least two nearby anchors. Three local TDOA values per anchor can be estimated by using the four antennas. The tag's data received by at least two anchors are transmitted to the server for joint processing by an improved TDOA algorithm. Since only local TDOAs from each anchor are required, all the anchors operate independent of one another, a feature that is extremely appealing with regard to the following:

a) System deployment and maintenance: the improved TDOA system is much simpler than existing TDOA systems because the spatially-distributed anchors do not need to be wire-connected (e.g., via optical fiber cables) to a common clock source for time-synchronization;
b) Required number of anchors: a minimum of 2 anchors are needed for 3-dimensional (3-D) positioning whereas the traditional TDOA systems require a minimum of 4 anchors for 3-D positioning;
c) Flexibility to increase the accuracy in 'hot' spots: if a higher accuracy at certain areas of the mine is required, it can be achieved by simply placing more anchors in the target area;
d) Flexibility to expand coverage area: expanding the coverage area can be achieved by simply deploying more anchors to the uncovered areas without affecting the already deployed anchors.

For common indoor environments (above ground), meter-accurate positioning typically requires the anchors' positions be precise to within a meter or so in a single coordinate system. For applications in underground mines, however, the positions of the anchors only need to be accurate relative to the structure of the mine (e.g., the sides of the mine tunnels). Also, even for cases when only 2-D location is needed, the vertical positioning of the anchors relative to the vehicle does not affect the normal operation of the system; that is, the anchor antennas can be mounted at the ceiling or sides of the mine tunnel. However, the anchors need to be strategically placed in the mine to ensure that the signals from a tag on a vehicle traveling along any path be received by at least two anchors simultaneously. If a tag's signal is received by more than two anchors, then the accuracy will increase. The asymptotic accuracy would best be obtained via experiments in the future for some specific mine geometries. Note that with the technology developed in this POC, anchors can be added to any location flexibly (more or less at will) to improve accuracy locally.

In line-of-sight (LOS) conditions, the distance between the anchors with the current POC system is estimated to be about 40m. A longer inter-anchor distance is possible by increasing the tag transmission power. However, deployment in actual mines will require optimizations that jointly consider tag transmission power, the propagation condition in the mine, the geometric structure of the mine, and the required vehicle position accuracy.

The red dots in Figure 1(a) imply multiple vehicle/tag positions; the network is able to simultaneously position multiple vehicles/tags in the mine. To enable autonomous vehicles, multiple tags will be attached to each vehicle, allowing the positioning system to estimate the vehicle's orientation and position, in addition to its instantaneous traveling speed.

Figure 1(b) shows all the major components including the RF anchors, RF tag, server, and a network hub. The server could be located in an office inside the mine. Data from the anchors are transferred to the server via the network hub. Data transmission between the anchors and server could be Ethernet or wirelessly (e.g., WiFi). If an Ethernet connection is adopted, then the anchors can also be powered by Ethernet. If laying Ethernet cables in the mine is difficult and wireless connection must be used, then the anchors need to be powered via other options. Thus the Ethernet connections shown in red in Figure 1(b) could be replaced by wireless connections. It is possible to use the WiFi node of each anchor to relay data traffic from other anchors to the server. To position fast-moving vehicles, however, using one anchor to relay the data of other anchors to the server may not suitable because relay will increase the positioning delay.

The network hub uses a wireless router that handles the data exchange and control command between the RF anchors, vehicle, and server. Each network node (WiFi nodes and Ethernet ports are all called network nodes in this report) is able to communicate to the other nodes through Ethernet or WiFi simultaneously. A WiFi network must be deployed throughout the mine, or deployed where autonomous vehicle navigation is needed. In this application, the high demand for computational power requires a high-performance server computer to handle the back-end processing. It includes real-time TDOA signal processing in parallel with sensor-aided location estimation, vehicle control feedback, and GUI display.

3.2. Positioning Hardware

The RF positioning hardware contains two elements: 1) a transmitter, known as the tag, and 2) a multi-channel receiver, also called the anchor.

The design of the tag, as shown in Figure 2(a), is a carrier card at the bottom with an ADRV9364-Z7020 attached on top. Together, they function as a software defined radio (SDR) that combines the Analog Devices AD9364 integrated RF transceiver with the Xilinx Z-7020 all programmable systems on chip (SoC). It offers a single RF receive path and a RF transmit path in the 70 MHz to 6 GHz range, allowing the development of the system in a very wide range of RF bands. The ADRV9364-Z7020 combines the RF signal path and high-speed programmable logic in one compact package and operates without additional modules.

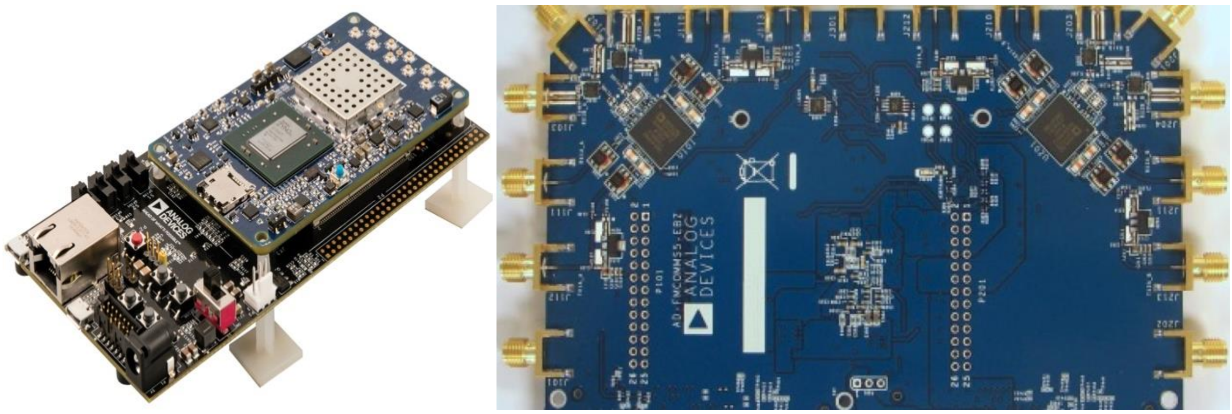


Figure 2: (a) The tag, ADRV9364-Z7020 attached on the supply board. (b) The analog front-end of the anchor, AD-FMCOMMS5.

The anchor hardware also comes with two PCB boards: an analog front-end (Figure 2(b)) and a digital back-end. The analog front-end is AD-FMCOMMS5-EBZ from Analog Devices. It equips dual AD9361 devices, each having two TX and RX channels which support up to four receiving channels. On each of the receiving ports, a dual band directional antenna is installed to retrieve the transmitted signal from the tag. The anchor hardware also operates from 70 MHz to 6 GHz, giving the most flexible selection of RF operation bands. The digital back-end is a Xilinx Zynq-7000 ZC702 evaluation kit, similar to the one on the tag. The ZC702 samples the signal from the analog front-end and sends it to the server, either via Ethernet or wirelessly.

Besides the TDOA positioning system, an IMU is investigated to improve the accuracy and detect the vehicle's initial attitude. The IMU with a standard I/O can be connected to the onboard microcontroller. Figure 3 shows the workflow of IMU (Model BNO055), which contains a three-axis gyroscope, a three-axis accelerometer and a three-axis magnetometer that provide a total of nine-dimensional inertial measurements. The IMU calculates the current position and direction based on the linear displacement and angular motion. The linear displacement is derived by double integration of the acceleration measurement. Then, the gyroscope and magnetometer data are combined using quaternion algorithm to calculate the heading direction of the vehicle.

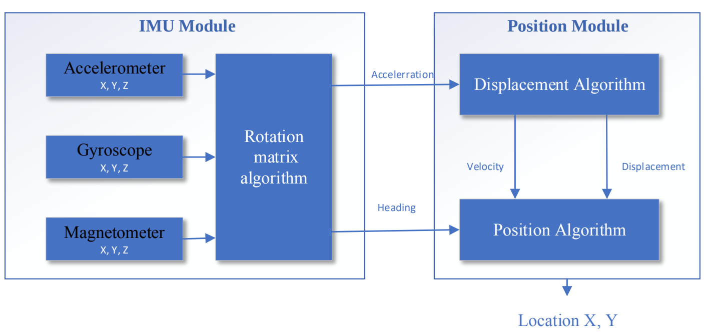


Figure 3: The inertial status calculation workflow of IMU BNO055.

3.3. GUI and Server Back-end

The first task of designing the server back-end is to identify the functions that the system needed. These functions can be grouped into two sections: 1) Graphical user interface, and 2) position and trajectory calculations. The server gathers raw TDOA data, calculates a current position and trajectory, sends directional commands to the vehicle and displays vehicle progress on the GUI (Figure 4).

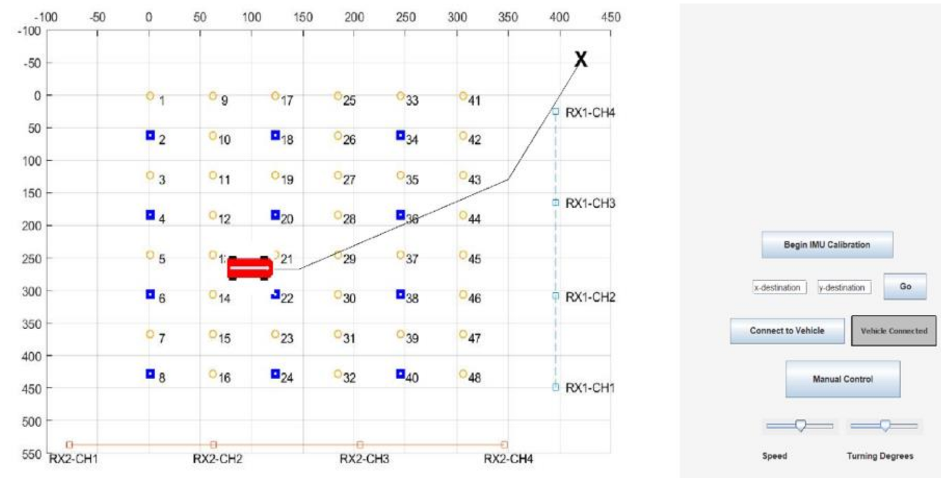


Figure 4: Graphical user interface with map and control buttons (*x*-axis & *y*-axis are in **centimeters**).

The GUI allows the user to select a destination to navigate, monitors the vehicle's position on the map as it drives through the mine and controls the vehicle manually when desired. The GUI makes two connections to the back-end and one connection to the vehicle. Once connected, the back-end reads the desired destination, starts the TDOA algorithm, calculates the vehicle's starting position, computes a trajectory to the destination, determines the directional commands needed to stay on the given trajectory and then sends those directional commands to the vehicle. To ensure each algorithm is computed with maximum efficiency, the back-end creates several sub-processes and threads to handle the most demanding tasks in parallel. The GUI also utilizes multiple threads to provide uninterrupted interaction with front-end features such as manual control.

3.4. Robotic Vehicle Design

The proof-of-concept underground mine vehicle frame was designed around the various on-board microcontrollers and sensors, putting the electronic functionality ahead of mechanical capabilities. The system was designed with four main parameters in mind: 1) spacious enough to host all electronic components, 2) lightweight for easy transportation, 3) modular for component swapping or add-ons, and 4) the ability to demonstrate basic movements for testing purposes. The current prototype built using a polyvinyl chloride (PVC) frame was adequate for lab testing. The rover's rocker bogie suspension was selected as an exceptional way to reduce weight while demonstrating limited all-terrain functionalities which have the potential to be built upon when moving from a proof-of-concept to a prototype vehicle.

A main functionality of this rover is its ability to navigate terrain common to mining areas. Mimicking NASA's Curiosity Rover, the underground mine vehicle uses rocker bogie suspension to straddle tall rocks and navigates unsteady terrain, illustrated in Figure 5. The front legs pivot independently from the rear legs, allowing each side to crawl over rocks while keeping as much contact with the ground as possible. This suspension eliminates the need for heavy and complicated spring or dampening without sacrificing maneuverability. Placing much of the rover's mass in the center with legs stretching far to the front and back makes it is nearly impossible for the robot to roll over itself while ascending or descending steep terrain.

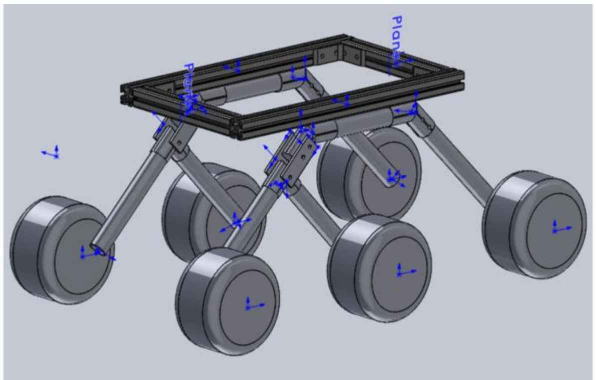


Figure 5: Preliminary model for the robotic vehicle.

4. Proof-of-concept Evaluation

The PoC evaluation has been carried out as the result of three subsystems: positioning hardware, GUI and control algorithm, and the robotic vehicle.

4.1. Positioning Hardware

The positioning hardware includes the RF transmitter and receivers and the IMU as a supplementary sensor. The objective is to primarily use the RF system to estimate the vehicle's position and examine the possibility of adding the IMU data to increase the overall accuracy.

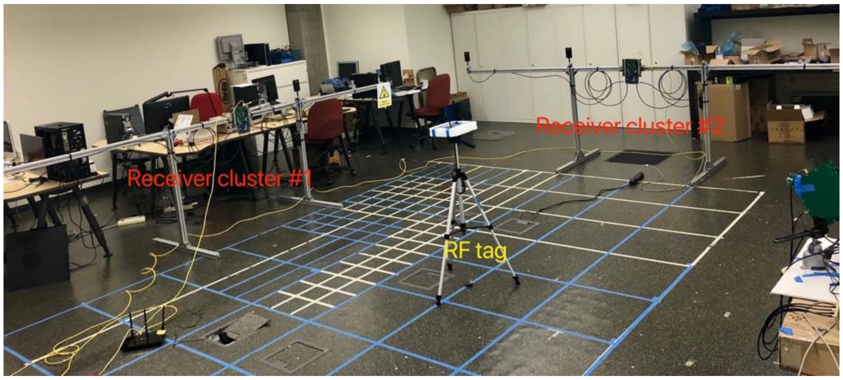


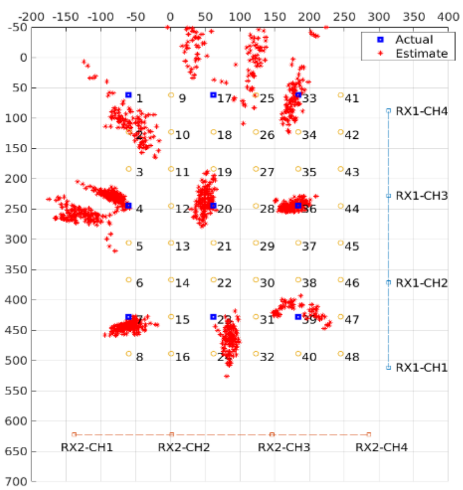
Figure 6: Test ground with two anchors and one RF tag.

Positioning and vehicle navigation tests have been conducted in a laboratory with an area of about 6 meters by 6 meters exclusively dedicated for these tests. Figure 6 shows the setup at the testing ground. The RF tag is configured to transmit a 56MHz bandwidth signal in a 5GHz RF band. The tag automatically starts transmitting a pre-defined data sequence when it is turned on. In order to deploy multiple tags in the same area and identify each one of them, the pre-defined sequences for each tag are unique. A 10,000 mAh rechargeable lithium battery pack is installed on the vehicle to power its motor and all onboard electronics.

Two anchors, each with four receive antennas, are mounted on two custom-made racks one placed along the north side and one along the east side of the test ground. For the new positioning algorithm implemented in this POC system to work effectively, the four antennas of each anchor must be physically separated. About 1 meter of distance between two adjacent antennas is sufficient, but increasing this distance generally leads to improved accuracy. However, the improvement will gradually diminish as the distance continues to increase. For example, increasing the distance from 1m to 2m will result in noticeable improvements whereas the benefits due to a further increase from 2m to 3m are negligible. In the test setup shown in Figure 6, the separation between two adjacent antennas on both racks is about 1.4m.

Note that if the mine geometry is a straight tunnel, then the anchors can be placed along the sides of the straight tunnel. In such cases, positioning the vehicle becomes a much simpler and easier task since it is effectively a 1-dimensional positioning case.

Some key metrics are used to define the positioning system evaluation outcome: 1) mean distance deviation from specified reference points, 2) mean distance deviation from specified paths. For the system test to be considered a success, values computed should not exceed one meter.



Test Point Index	Median Error (meter)
# 01	0.531894
# 04	0.569268
# 07	0.319086
# 17	1.081355
# 20	0.393297
# 23	0.479004
# 33	0.269442
# 36	0.282392
# 39	0.375715

Figure 7: (a) Estimates at reference points (*x*-axis & *y*-axis are in **cm**). (b) Mean distance deviation at reference points.

Experiments of the RF system are compiled from two parts, a stationary test and a moving test. Stationary tests refer to the case when the RF transmission tag mounted on the robotic vehicle is at a fixed location (no motion) when its position is estimated; moving tests refer to the case when the robotic vehicle with the RF tag is moving while the trajectory is estimated. All the final postition is smoothed via a median filter to eliminate any outlier.

First, the RF tag is placed at multiple reference positions (separated about 1.2-1.8 meters) selected across the test ground. The results are obtained when the transmission tag mounted on the vehicle stays still at each reference point. The stationary test result is visualized in Figure 7. Figure 7(a) shows the estimated position at sepcified reference points, and (b) lists mean distance deviation at the test points. The median error is calculated from 300 estimations at each test point. Note that although the tag stays still at one point, noise and environmental changes such as motion of people will introduce some randomness in the estimation results, causing the variance. The mean distance deviation at these nine test points ranges from 0.3 to 1 meter. Second, the RF tag is installed on the robotic vehicle shown at the lower-right corner in Figure 11(b). The vehicle is manually navigated through arbitrary trajectories. The estimated points are continuously recorded and displayed on the GUI.

For the moving test, due to safty issue and constrained test area in the lab, the vehicle's speed is limited under 1 meter per second, in the test ground as shown in Figure 6. The moing test result is obtained when the robitc vechicle is controlled to drive through a certain path. Figure 8 shows the distance deviation of the estimated positions compared to the actual movement as the vehicel moves in a straight line and a 100-degree right turn. Most of the estimated posistions landed up within a 1 meter range of the actual vehicle moving trajectory. The density of the estimated positions reflects how fast the vehicle passes each position. In Figure 8(a), the densely plotted points around #21 indicates that the vehicle has a brief stop at this point.

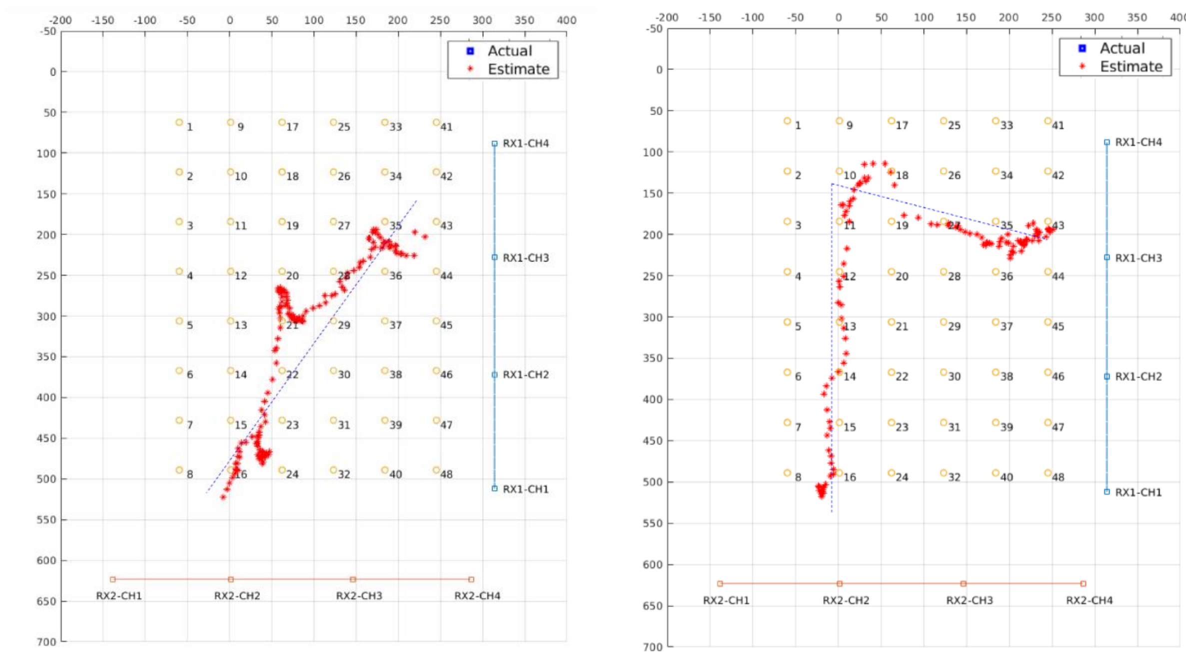


Figure 8: Distance deviation from specified path (*x*- axis & *y*-axis are in **cm**): (a) a straight line; (b) a 100-degree right turning.

While the test results are obtained in a small space (about 6m x 6m of dedicated experimental space inside a lab of about 10m x 12m) as shown in Figure 6, in full-scale deployments (e.g., anchors are placed about 40 meters apart), about 1m of positioning accuracy can still be maintained conditioned on: (a) tag transmission power is sufficiently high so that the signal-to-noise ratios at two or more anchors are sufficiently high; (b) the minimum separation between the antennas of the same anchor is at least 1m (≥2m would be ideal). Factors that dominate the positioning accuracy include: (a) signal bandwidth, (b) number of anchors that can receive the signal of a particular tag simultaneously (see discussion in the 6th paragraph of Section 3.1), (c) separation of the antennas of the same anchors (see discussion in the 3rd paragraph of Section 4.1), and (d) the environment (for example, presence of substantial amount of metallic objects will create significant multipath which affects the accuracy).

The IMU is considered as an add-on to the RF positioning system. Some experimental tests are completed to evaluate the IMU performance. The IMU is connected to a microcontroller that processes the sensor measurements and sends them to the server wirelessly. With these data, the server back-end estimates the IMU’s position and moving trajectory.

A circular trajectory and a square trajectory are chosen for the IMU tests, since the performance for these cases would be sufficient to predict the performance of any arbitrary moving trajectories. The results are shown in Figure 9: (a) when the target moves along a circular path with a radius of 1.5 meters, and (b) when the target follows a square path around 1.5 meters by 1.5 meters. At this point, blending IMU data with RF data has not been completed yet.

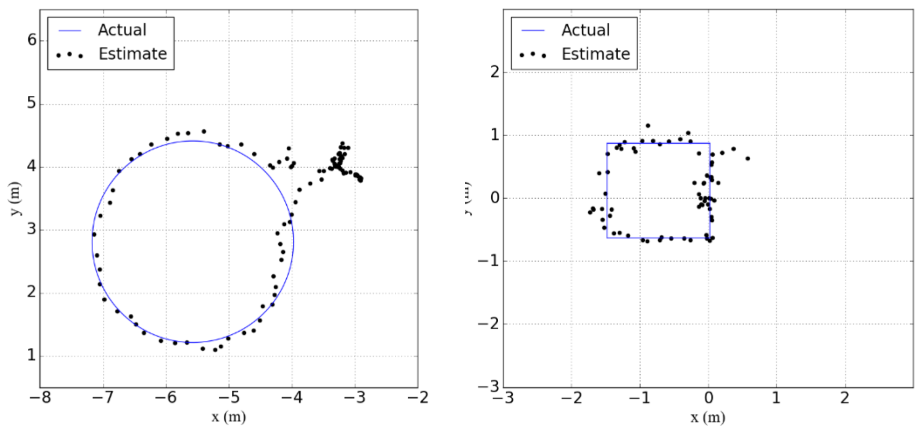


Figure 9: IMU estimated vs. actual trajectories: (a) circle with 1.5-meter radius; (b) 1.5 meters by 1.5 meters square.

4.2. GUI and Control Algorithm

The system logic block diagram is shown in Figure 10. They are three main blocks: 4-CH receiver (RF anchor), VEHICLE and SERVER. The GUI and back-end control code are hosted on the SERVER block. The GUI makes connections to the back-end for sending and receiving position and trajectory information. For position information, the vehicle's current position and heading direction are updated on the GUI. For trajectory information, the calculated trajectory from the vehicle's current position to the final destination is drawn over the map and allows the user to visualize the vehicle's planned route as it traverses its environment. The GUI also allows for manual calibration of the IMU at the beginning of operation in order to better accommodate future development. The GUI is developed using Java which allows runtime on all major operating systems (Windows, Mac, or Linux).

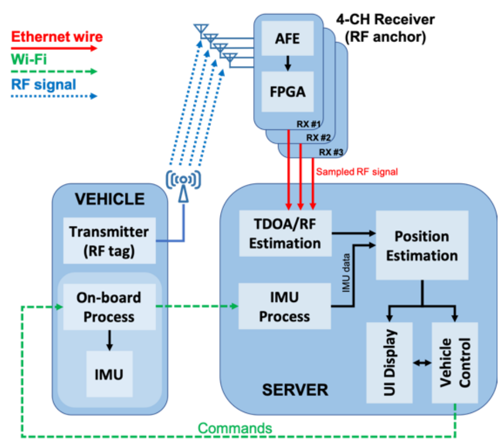


Figure 10: System logic block diagram.

All programs ran on the server that provides information to the GUI and vehicle is defined as the back-end control algorithm. The position estimation algorithm gathers and processes raw data from the TDOA and then calculates the current position and heading direction. The vehicle control algorithm takes the position and heading direction to calculate a route to the destination and navigate the vehicle.

The back-end utilizes several threads and processes to increase computational efficiency. The TDOA algorithm operates in a dedicated process for true simultaneous runtime while less demanding functions such as back-end to front-end communications are handled via dedicated threads for sending and receiving messages. The five most recent coordinate estimates are used to calculate a moving average and to find the vehicle's position. A history of positions is used to calculate the vehicle's heading. Once the current position and heading has been determined, a trajectory algorithm finds several points between the vehicle and the destination. Directional commands are then sent to the vehicle to navigate towards the nearest point in the trajectory. When the vehicle is within a range of a given point, the next point is navigated to. This process is continued iteratively until the vehicle reaches its destination.

4.3. Robotic Vehicle Manufacture

As shown in Figure 11 (a), a sturdy aluminum enclosure in the center of the vehicle protects electronics while the PVC legs mount to slots on the outside of the frame. These slotted aluminum bars allow the center of gravity to be adjusted by sliding the legs forward or backward as necessary. The slots also provide easy attachment for additional components such as antennas. Schedule 80 PVC tube is chosen to build the legs for its strength-to-weight ratio as well as its ability to conceal wires assemble rapidly. Only two varieties of bolts, 1/4” and 5/16”, are used to fasten the frame together, keeping the required assembly tools to a minimum. The four motors driving the corner wheels are selected to allow a payload of 18 pounds in addition to the weight of the frame at a speed of 2.5 meter per second.

All the electronic components on the vehicle are hosted within the aluminum enclosure. In Figure 11 (b), the picture shows the placement of the vehicle controller, motor controllers, battery pack and RF tag. Note that in the tests the signal radiation point of the RF tag is not where the RF tag board is as shown Figure 11(b); instead, a cable is used to connect the RF tag antenna and the tag board, and the antenna (tag signal radiation point) is mounted on a vertical pole of the robotic vehicle.

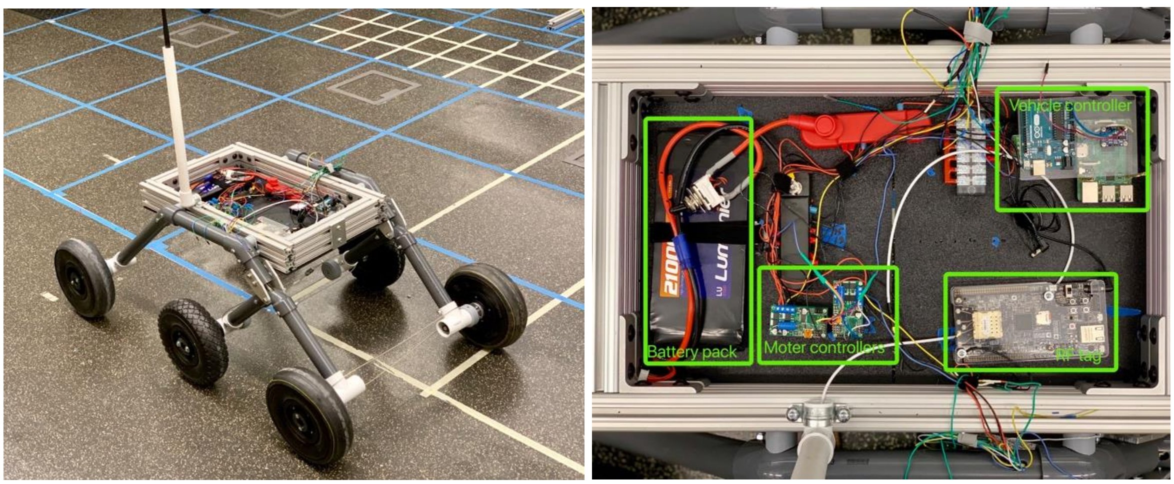


Figure 11: (a) Fully assembled robotic vehicle. (b) Electronic components installed on the vehicle.

Both manual and autonomous controls are tested after the robotic vehicle has been fully assembled at the test ground. The server and the vehicle are connected to the local network hub as shown in Figure 1(b). There are three steps to start the vehicle-to-server communication: 1) start the vehicle control program on the vehicle controller, and 2) open the autonomous vehicle interface on the server, and 3) establish a TCP connection between the vehicle and the server. Once the vehicle's connection status ON is displayed on the GUI, the server takes control of the vehicle.

The objective of the manual control test is to ensure the vehicle can operate manually and to test the vehicle's driving ability. The speed and turning degrees can be adjusted to fine-tune the manual control settings. The arrow-keys on the server computer are used to control the vehicle's movements. There are eight vehicle maneuvers: forward, backward, left, right, forward-left, forward-right, backward-left, and backward-right. The manual control test is considered passed if the vehicle can be turned in the eight directions listed above.

The manual control test result indicates the vehicle is capable to perform all designated maneuvers. However, a problem that occurs with a 25% probability in which one of the four motors will not rotate when commanded to rotate by the server. It has been determined that this problem is caused by the motor controllers incorrectly reading a serial command from the vehicle controller and can be addressed by replacing the 18v25 Motor Controllers with the more-reliable VNH5019 motor drivers. This update is currently being performed.

The objective of the autonomous control test is to ensure the vehicle can navigate to a given point autonomously. Follow the same procedure to enable the vehicle-to-server connection, then enter the coordinates of the destination on the GUI (Figure 4). The vehicle will begin to autonomously navigate to the given position. The trajectory is displayed on the map and updates when the vehicle's position changes. The vehicle will stop when the vehicle is within 1-meter range of the desired position.

The autonomous control test has positive preliminary results demonstrating the ability for the vehicle to drive autonomously for a few meters. When the trajectory algorithm is completed, the autonomous test will be performed again with the vehicle navigating to a user-selected destination.

5. Technology Readiness Assessment

5.1. Positioning Hardware

The results are within expected specification. The current hardware can be improved in three ways to improve the system for commercial use: a) the tags can be made a lot smaller in size without most of the functionalities provided by ADRV9364-Z7020 that emulated the tags in the POC system. It will achieve the same accuracy as required to guide the autonomous vehicle, but it will be a much smaller and cheaper. The major goal of redesigning the tag is to make it possible to transmit at a higher power level (current tag transmits at 10 dBm; using ISM band up to 30 dBm average power can be transmitted), so that anchors can be spaced 50-100 meters apart. But as stated earlier, a main attraction of the proposed solution is that that anchors operate independently. Thus, if for any reason certain spots in the mine require a higher positioning accuracy, more anchors can be added without affecting achors already deployed, making it very flexible to optimize a network.

The current hardware to emulate the positioning anchors is a combination of two evaluation boards, one by Xilinx and one by Analog. These are very expensive. This design can be made in a single PCB with significantly reduced costs without compromising on the performance. Also, using USB or Ethernet as an power option is critical for deployment underground mines.

The estimated position from the RF system is reported as discrete values. A sensor-aided IMU is under development to improve continuous tracking of the vehicle. The circular IMU-movement test proves the feasibility of combining IMU position-tracking with the TDOA system in the future. Additionally, the encoder can be added as another sensor, which can be attached on the vehicle motor to act as a speedometer.

5.2. GUI and Algorithm Development

Prior to proceeding towards developing a prototype, a blending algorithm can be developed to increase the accuracy of the positioning system. The wheel encoders and IMU data can be incorporated into the TDOA data to increase position accuracy. The trajectory algorithm can be improved by incorporating obstacle avoidance with route calculations. The TDOA positioning algorithm can generate more estimates per second by converting raw data processing from Matlab to C++ or Python. Currently all the data acquisition is implemented in Python, but constrained by time and technical resources, for positioning, we had to build on the previous Matlab codes. This requires us to perform a time-costly data-exchange between Matlab and Python on the server, which slows down the positioning update rates, and reduces the positioning accuracy.

Features can be added to the GUI to perform autonomous driving procedures and log test data for post-test evaluation. With a camera mounted onto the vehicle, a video feed can be integrated into the GUI for live vehicle monitoring. The vehicle control software can be updated to incorporate motor feedback which would provide a higher degree of vehicle control. Manual vehicle control can also be improved by the use of a dedicated handheld vehicle controller.

One of the goals is to specify any arbitrary moving trajectory to a destination for the vehicle, and the system must guide the vehicle along the specified trajectory to the destination, achieving “autonomy” of the vehicle. While all the essential pieces of information to achieve this goal are there, the algorithm that takes the specified trajectory and real-time positions of the vehicle still need improvements for commercial use.

5.3. Robotic vehicle Design and Manufacture

The purpose of the prototype vehicle is to exhibit the functionalities of the remote positioning system while testing the effectiveness of the rocker bogie suspension for potential commercial use. With these goals, the frame is largely a success. However, the current polyvinyl frame leads to the structural problems listed below that could affect the positioning results:

1) **Wheel deflection**. Mounting the legs at a single point on the aluminum enclosure does not constrain the extended legs but leads to an outward-bowing effect. As the rover moves, especially rotating in place or changing direction, the legs gradually move outward. With nothing restraining them, the wheels deflected from their original position up to 3 inches on either side, for a change of up to 6 inches. The rover began to turn more slowly and with less accuracy. This problem is provisionally solved using tension wire between the front legs, reducing the change in wheel position to less than 1 inch.

2) **Wheel Slippage**. During high acceleration movement, the wheels occasionally slipped in place causing the rover to take more time to reach its destination. Both the wheels and testing floor (vinyl tile) are made of hard materials, resulting in low traction for the vehicle to make quick accelerations.

The largest mechanical improvement to the vehicle frame would be upgrading the polyvinyl parts to more sturdy materials such as carbon fiber, aluminum, or a steel alloy to prevent leg deflections and improve rigidity. The current concept successfully functions as a mode of transport over rough terrain for various mining attachments such as a spotlight, cameras, or a robot arm. With one design iteration to reflect on, the underground mine rover team can improve the design by: 1) Purchasing wheels with larger ground to wheel surface contact area to improve traction. 2) Upgrade the leg structure with more rigid components such as carbon fiber, aluminum, or a steel alloy, and 3) increasing the carrying capacity of the vehicle.

5.4. Potential Demo Setup for Assessing Prototype Implementation Readiness

Although the PI's team had not found an actual mine to perform tests of autonomous location-guided navigation of the robotic vehicle, after numerous attempts, office building hallways (see for example Figure 12) may be used to emulate mine tunnels for prototype implementation readiness assessments. Specifically, positioning anchors will be placed along the hallways to cover 100-200 meters of the hallways. On the server a user will specify a trajectory along the hallways for the robotic vehicle to follow. If the location-guided autonomous vehicle is able to follow exactly any traveling trajectories specified for it, then the test is considered a success.

Figure 12: Office

6. Appendices

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