Experiments in real-time map-based underground global positioning

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Abstract

The satellite-based global positioning system (GPS) has significantly changed the way site operations are carried out in surface mining. The GPS has impacted safety, productivity, fleet efficiency, and maintenance practices. However, no comparable global localization system exists for underground mines. This paper discusses recent work in the application of ideas from the mobile robotics research community to the problem of real-time vehicle positioning in underground drift networks. Related previous work recently focused on the creation of globally consistent 2D maps of underground environments that possess sufficient detail to be used for underground localization. Our current work entails the development of a GPS-like system for mobile mining equipment, with results given from both laboratory and field experiments.

Biographies

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1 Introduction

The satellite-based global positioning system (GPS) is widely employed in surface mining to improve efficiency, increase safety, and streamline operations. GPS signals however cannot be used in underground environments such as in tunnels and mines. Furthermore using time-of-flight radio-based localization is problematic in underground environments due to severe multi-path issues, comparatively poor accuracy and cost. A relatively inexpensive underground positioning system that would allow mining operations to accurately monitor their vehicles—in real time—as well as allow operators working in the mine to accurately know the position of all mining vehicles could benefit, for example, safety and efficiency. This paper presents the current status of research into a map-based approach to building such a real-time global underground positioning system for mining vehicles.

The underground positioning system presented here is designed to enable underground mining vehicles (driven by human operators) to localize itself in real time on an *a priori* known map, similar to that of a truck driver using GPS to localize on surface. In this system, no significant infrastructure is installed in the mine besides sporadic passive radio frequency identification (RFID) tags. Several design goals were set for the system presented here; it must: (a) be capable of working in a large-scale environment (tens of km); (b) use high-resolution metric maps (cm-range); (c) not require human input during localization; (d) have low computational requirements; and, (e) be accurate, robust and have a fast update rate.

1.1 Existing Technologies

Although not the first, Marshall et al. (2008) presents an autonomous tramming system for LHD vehicles. The vehicle is manually "taught" a path for which a set of overlapping "atlas" type maps are created. The vehicle must always start in the same location as the path since it has no global reference for its location. This system is available commercially, but its use is specific to local repetitive hauling since creating and testing a new path can be time consuming. Thus, this system, like other autonomous tramming systems, does not permit a vehicle to *globally* localize itself in the underground environment like GPS does on surface.

Other commercially available localization systems use active RFID or Wi-Fi transmitters that are mounted on vehicles to estimate their location. Many mining companies are familiar with these products. RFID readers installed throughout the mine detect nearby tags and measure a received signal strength indicator (RSSI). Several limitations exist for this approach. Radio signal readers must be strategically installed at fairly short distances so that each tag is detected by multiple readers. Furthermore, signals in underground environments bounce off the walls leading to multiple signal paths, which can combine constructively or destructively, leading to erroneous location estimates. The maps used for displaying the localization information are normally CAD-drawn maps with the RFID readers locations simply marked on them. For additional discussions about existing technologies, see also Artan et al. (2011).

1.2 Overview of the System

In robotics literature, researchers such as Pathanawongthum and Chemtanomwong (2010); Zhang et al. (2010) use dense arrays of RFID tags and their RSSI to perform localization. The patterns, spacing and large number of RFID tags used in a small area make those approaches impractical in a large scale underground environment. The work presented in this paper does not use the RSSI. RFID readers are installed on vehicles being localized and cheap passive RFID tags are only used sporadically (spacing of 50 to 300 m) with the only requirement being that the RFID tags remain static. Furthermore, the RFID tags are installed without any measurements (i.e., their locations do not need to be measured).

This paper builds on the work found in Lavigne (2010); Artan et al. (2011), where the goal in that work was to produce globally-consistent metric maps (i.e., survey-like maps) of unstructured and very large-scale environments. That work built on the method from Lu and Milios (1997) for enforcing consistency of the map by recognizing similar scans taken by the range measurement devices and by performing a global optimization over a "closed-loop" set of pose estimates.

In the work presented here, a particle filter is used for localization. This method is based on recursive Bayesian filtering and has been shown to work successfully in localizing robotic vehicles Thrun (2002). The method consists of using particles to represent the posterior localization estimate. Each individual particle represents one possible vehicle pose. In this paper, the environment is assumed to be flat (2D) and changes in elevation are not measured or accounted for at this time. As shown in Gutmann et al. (1998); Gutmann and Fox (2002) particle filters can be very robust, can globally localize a vehicle and can recover from a "kidnapped" vehicle situation. The implementation of the particle filter largely follows the current literature with the exception of the introduction of RFID tags for global localization and the use of occupancy grid maps incorporating RFID tags. These topics are discussed in the next section of this paper.

2 Algorithms

This section presents an overview of the algorithms that make up the system. As mentioned previously, a map is required first. A convention was developed wherein passive RFID tags are not installed in intersections, but only in drifts. This facilitates mapping and localization algorithms. Data is first collected for mapping by driving a sensor equipped vehicle (see Section 3.1) through the underground environment. As the vehicle is initially moving in the tunnels collecting sensor data, RFID tags are detected sporadically. The RFID tags are then used as unique markers to segment the data into pieces that start and end with detected RFID tags. Mapping the environment can thus be done in sections. Using the RFID tags and laser scan matching, all the maps can be arranged to form a global map of the environment; see Lavigne (2010).

2.1 Node Maps

The type of map currently used for localization is referred to as a *node map* and is illustrated in Figure 1. Each RFID tag has an associated node map that consists of all tunnels that connect it to every other directly reachable RFID. If a vehicle is initially at an unknown location, detecting an RFID would place the vehicle on that tag's associated node map, in the detection range of the RFID. If a compass was used during mapping, the orientation of the vehicle is also (very roughly) known. A particle filter can be initialized and the vehicle location can be tracked in the current node map.

2.2 Jump Locations

Since the global environment is represented by smaller node maps, it is necessary to quickly track the pose of a vehicle over many node maps as the vehicle traverses the environment. The discrete step of moving the estimated pose of a vehicle from one node map to another is referred to as *jumping* node maps. Jumping from one node map to the next is essentially a change of coordinates. When jumping node maps, particles must remain at the same physical location which is described slightly differently by the new node map (a

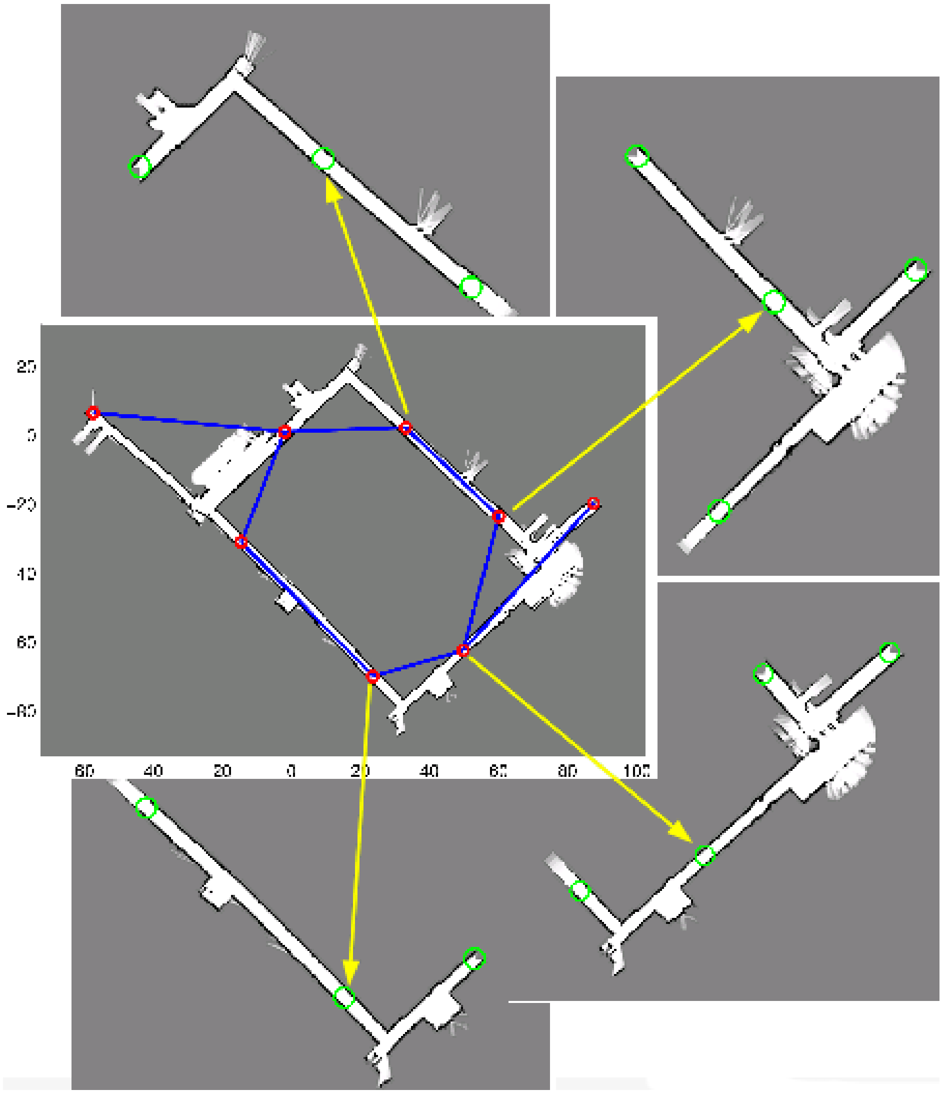

Figure 1: An example global map (center) and node maps for each RFID tag.

rotation & translation must be performed). Jumping node maps can decrease the accuracy of the estimated vehicle location and in a worse case scenario it can cause localization to diverge after a jump.

2.3 Global Localization

An underground vehicle's navigation system might be turned on in any part of the mine. Kilometre-long tunnels, poor lighting, and featureless walls can prevent even a person relatively familiar with the environment from knowing their precise start location without specific indicators. For a sensor-equipped vehicle the presence of static unique RFID tags in the environment enables solving the global localization problem when a tag is detected. The vehicle location is then known with an error equal to the maximum range of the RFID tag reader (e.g., a few metres). These tagas greatly simplify the localization algorithm since the problem no longer scales with the size of the environment.

To simplify the underground global positioning problem even further, the direction of travel of the

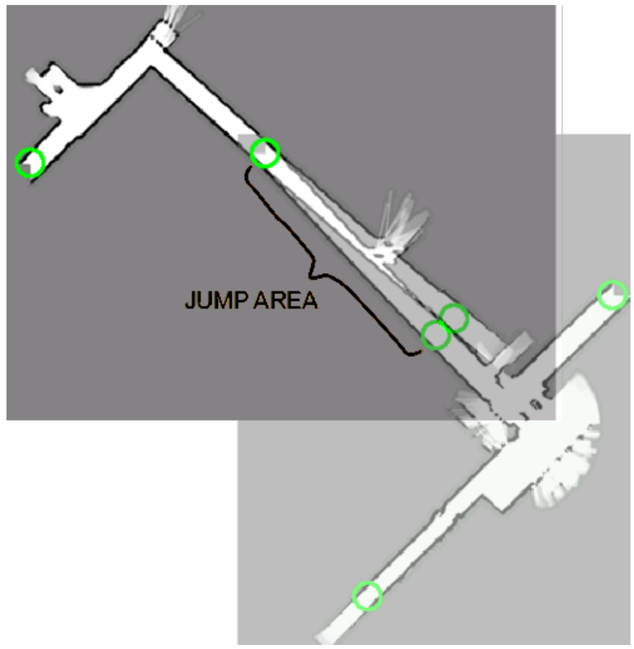

Figure 2: Where node maps overlap the localization algorithm can jump node maps.

vehicle can be estimated from an on-board digital compass. By comparing the compass data with the node map's North direction, the heading of the vehicle is obtained. Given that RFID tags are placed by convention in tunnels, the compass accuracy must only be better than +/- 90° in order to solve for the direction of travel. Tracking the vehicle's precise position and orientation can then be done using the particle filter. For brevity's sake, details about the particle filter are not provided here. The reader is referred to Fox et al. (1999) or any of the many other references available about particle fitlers.

3 Experimental Deployment

This section describes preliminary experiments in an underground environment at Carleton University. Deployment of the localization system consists of the following steps:

1. Passive RFID tags are attached to the tunnel walls or infrastructure every 50 to 250 m, depending on the environment; their location need not be measured.

2. A sensor-equipped vehicle is driven throughout the underground environment to collect data for mapping purposes; maps can be easily updated at anytime by driving the local area.

3. The logged data is then processed offline and the generated node maps are downloaded to all sensor-equipped vehicles.

4. The vehicles can then be driven through the tunnels and their location is shown, in real time, to the vehicle's operator (like GPS on surface).

Further to the above, if a Wi-Fi network is available underground, vehicles can relay their position to be shown in real time to every other vehicle as well as on surface. The activity of all sensor-equipped vehicles in the mine can be monitored remotely using the MineView (www.mineview.ca) interface from any web-enabled computer or device.

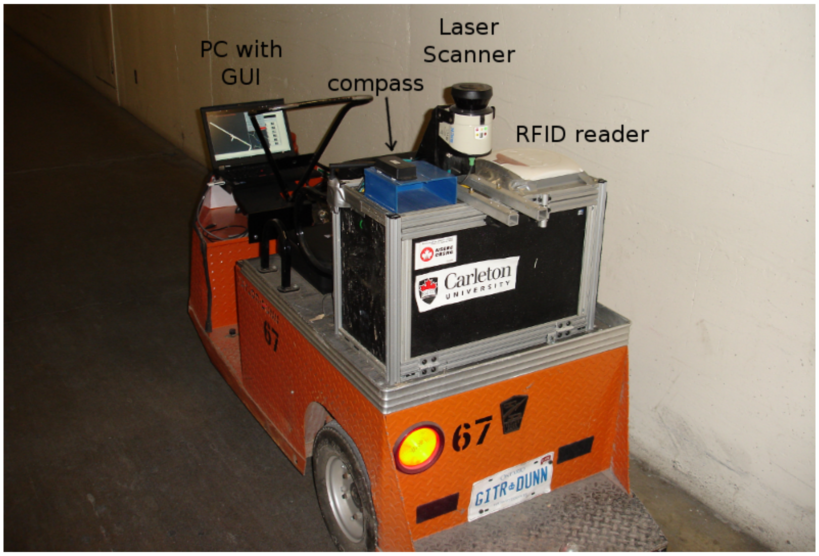

Figure 3: Custom-modified Taylor-Dunn SS-534 vehicle in the tunnel network.

3.1 Prototype Hardware

For preliminary testing, a Taylor-Dunn model SS-534 industrial vehicle was equipped with two US Digital A2 optical encoders recording the steering angle and wheel rotations, which are used as odometry measurements. A rear-facing SICK LMS 111 laser range finder provided range measurements over a 270° field of view, and an Alien ALR-9650 EPC Class-1, Generation-2 RFID reader was used to sense nearby RFID tags mounted on ceiling light covers. The passive tags used were Alien ALN-9654 EPC Class-1, Generation-2. A digital compass module HMC6352 was used to detect the local magnetic field vector relative to the vehicle pose. A custom real time data acquisition system was used to collect data at a rate of $\sim$20 Hz from the sensors. The vehicle is shown in Figure 3. A Thinkpad laptop featuring an Intel Centrino2 (2.26 GHz) processor was used to run the on-line particle filter algorithm with an average of 1000 particles at $\sim$10 Hz.

3.2 Online Testing in the Carleton Tunnels

The Carleton University campus is connected by a network of underground tunnels, illustrated in Figure 4, with an average width of about 4 m. This offers a good testing environment for an underground localization system. Although not exactly like an underground mine, it has many characteristics that make it even more challenging. The localization system was implemented on a laptop and a front-end graphical user interface (GUI), resembling a car GPS unit, was developed such that meaningful information about the vehicle pose and status could be shown in real time to the vehicle operator.

4 Results and Discussion

Screenshots of the localization system's GUI are shown in Figure 5. It updates at a rate of 10 Hz. The estimated vehicle pose is shown using a vehicle icon in the centre of the node map. The vehicle location is also shown on the global map on the right side of the screen along with the area covered by the node map view. The current laser range finder measurements from the vehicle are projected from the estimated vehicle

Figure 4: Photos from the underground tunnel network at Carleton University.

pose and show a good localization estimate if they overlap with the map walls (for testing purposes). The circles represent the detection area of RFID tags and the thick circle indicates the current node map in which the vehicle is being localized. As can be seen in Figure 5, the vehicle jumps from one node map to the next as it is being driven at 11 km/h. The first picture shows the node map corresponding with the top RFID tag while the second picture shows the vehicle is on the bottom RFID node map.

The localization system has been successfully tested in kilometre-long runs through the Carleton University tunnels. The web interface, was successfully tested such that, where available, the vehicle connects using Wi-Fi to the server and regularly sends its position and status. This map-based data is displayed by the server to any web enabled device, anywhere in the world. The technology could be used to enable route planning and for off-site management to observe live activities in the mine. Moreover, the specific locations of all equipped mining vehicles would be available on the web server in the case of an emergency.

4.1 Accuracy

Experiments have been carried out to estimate the range of mapping and localization errors in the Carleton tunnels for the current setup. Since GPS can not be used, distances between walls and corners in a section of the tunnels were measured and the measurements were compared with the associated node maps. The biggest mapping error found was +1.57 meter for a 67.5 meter long tunnel (+2.3%). The vehicle was also driven through the tunnels and at specific locations the vehicle was stopped and its estimated location with respect to the map, as reported, was compared with the physical distance as measured with respect to the tunnel corners and walls. The biggest localization error found was -1.0 ± 2.14 meter in the tunnel with the biggest mapping error. Clearly, many factors influence the localization error and any objective error measurement test will only be representative for the particular combination of environment, map, sensors used, speed and path driven, wall features, algorithm parameters, floor roughness, etc.

5 Conclusions and Ongoing Work

This paper has reported on a 2D localization system for underground environments. The efficient use of RFID-based node maps allows for truly large scale underground mapping and localization, with an accuracy

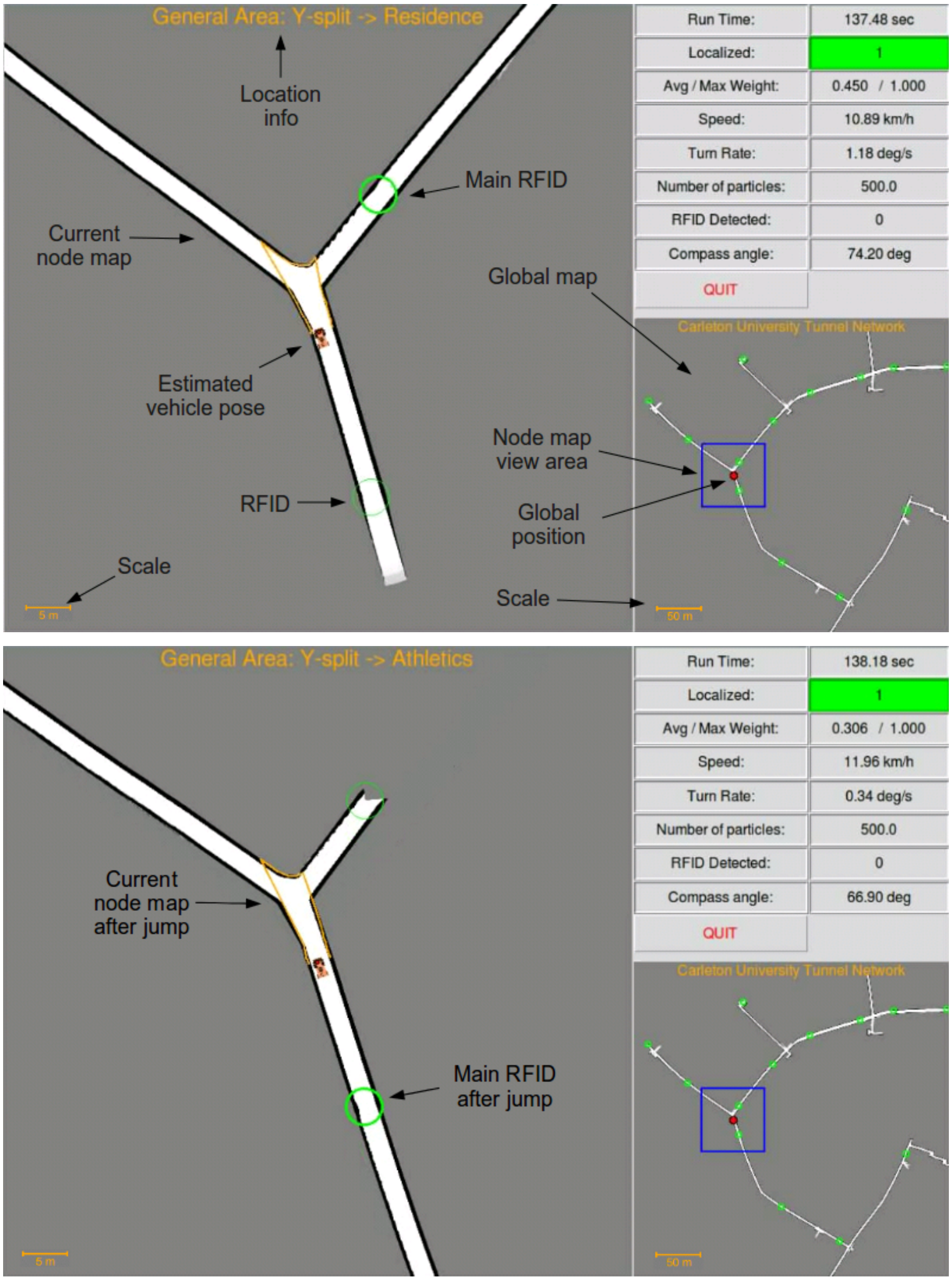

Figure 5: Screenshot before and after vehicle jumps node maps in the Carleton tunnels.

of a few decimetres using an average computer. A GUI and web interface for the system was designed and tested, which shows the location of sensor-equipped vehicles in real-time on any web enabled device. Experimental results from online localization over kilometre-long runs in the Carleton underground tunnel network were presented. The authors believe that the presented approach might lead to an enabling technology that would support many positioning applications in underground mines.

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