Term Project
James Walker
CS5461
Executive Summary

Autonomous navigation presents a challenging problem in the field of robotics. One of the challenges involved with autonomous navigation is enabling robots to determine their location within their environment. Existing solutions are typically expensive, such as several-thousand-dollar lidar sensors. We present a cheaper, yet still performant alternative utilizing radio frequency identification (RFID) tags. By equipping each robot to be tracked with an RFID tag and setting up at least three RFID readers, the location of each robot can be determined using a multilateration calculation. Additionally, since the locations of all robots are stored in a single, centralized database, the system can also be made to coordinate the actions of all tracked robots instead of forcing them to act independently.
# Table of Contents

1. Introduction: Application Domain ................................................................. 4  
2. System Overview .............................................................................................. 5  
3. Hardware .......................................................................................................... 5  
4. Database ............................................................................................................ 7  
5. Client Application ............................................................................................ 8  
6. Graphical User Interface (GUI) ........................................................................ 10  
7. Conclusion ......................................................................................................... 11  
References ........................................................................................................... 13

# List of Figures

1. Minimal database configuration ................................................................. 7  
2. Illustration of multilateration ........................................................................ 9
1. Introduction: Application Domain

Autonomous navigation presents one of the greatest challenges in the field of robotics. The problem of creating a robot that can reliably determine its own position and orientation, identify local topographical features, and plot movements through its environment is far from trivial. The problem becomes more difficult if multiple robots must work in tandem in a topographically complex environment; for example, on a factory floor that makes use of multiple mobile robots to aid construction processes. In this case, the robots must also be aware of each other's locations, and the efficiency of their navigation could be enhanced if they coordinated with each other.

We present here a system for efficiently solving one aspect of this problem, that of determining the location of an arbitrary number of robots within an arbitrarily large space. Our solution would also be useful for solving the problem of coordinating robot actions because it stores the locations of each tracked object together, such that a central algorithm could compute paths and return them to the robots, or the complete location information could be transmitted to each robot so they could independently compute movement actions with mutual awareness of each other's locations. Although the problem and solution are formulated in the context of robotics, and particularly process automation, this approach could be generalized to work with any scenario where simultaneously tracking the locations of an arbitrarily large number of objects is useful.
2. System Overview

In this system, each robot (or other object to be tracked) is equipped with a single active RFID tag. Enclosing the tracked space are at least three active readers clocked at 3 GHz. Every reader is connected to a single centralized computer with a MySQL database for recording position data. The database is connected to a terminal, either local or remote, which displays a map showing the locations of all tracked objects and provides the user the ability to enter additional information.

Each reader queries all tags in range at an appropriate rate. Because each tag's response travels at the speed of light and each reader is clocked at 3 GHz, the system can then use multilateration to approximate the location of each tag with an accuracy of 10 cm. This data is then forwarded to the database, where it can be displayed to a human supervisor, used for calculating coordinated movement actions, and forwarded back to each tracked robot.

3. Hardware

Every object to be tracked is equipped with a single active read-only RFID tag. Each tag contains a serial number that uniquely identifies the object to which it is attached. The tags are active to provide greater range; with additional batteries, they can achieve a transmission range of over 100 meters. They are read-only because it is never necessary to update their information, as each object's uniquely identifying serial number will never change.
The tracked space is enclosed by active readers which are clocked at 3 GHz. Each reader queries all RFID tags in range at an appropriate rate. For many applications, a rate of 10 times per second would probably be more than sufficient. By being clocked at 3 GHz, and knowing that the incoming and outgoing signals travel at the speed of light (approximately $3 \times 10^8$ m/s), each reader can calculate the travel distance from each tag to an accuracy of 10 cm. With a minimum of three readers, multilateration can then be used to calculate the three-dimensional coordinates of every RFID tag to within about 10 cubic centimeters. With additional readers, the accuracy of this calculation could be refined. Additionally, by placing readers across an extended area, any space which is in range of at least three readers can be considered part of the tracked space. Thus, the tracked area can be expanded to an arbitrarily large size simply by adding more sensors.

Position data gathered by the readers is forwarded to a single centralized system and recorded in a database. The centralized system is connected to a wireless network so that either the position data, or movement actions, or both can be wirelessly forwarded to the robots. If the central system is used to calculate coordinated actions for every tracked object, then it should run on hardware robust enough to perform these intensive computations in real-time.

Lastly, the central system is connected to a local or remote terminal. This terminal requires a monitor and user input (keyboard, mouse) because it is used to display a real-time map of the tracked space and all the objects within it, and to enable a human supervisor to update extra information about the system as necessary.
Note that if multiple RFIDs are using the same frequency band, as is likely, additional measures will be required to prevent the signals from interfering with each other. If it is feasible based on limitations of other parts of the system (such as the ability of the database to update rapidly), a form of Time Division Multiple Access (TDMA) could be used by increasing the transmission rate of the readers and having RFIDs be active only during certain time slots. However, this would require a high degree of synchronization. Alternatively, Code Division Multiple Access (CDMA) could be used to relax the synchronization requirement.

4. Database

The system uses a simple MySQL database. Given that only a small amount of data is being tracked (X, Y, and Z coordinates), queries will be completed quickly enough to allow real-time position tracking even if tracking a large number of objects. In order to implement the system described herein, only a very minimalistic amount of data needs to be tracked. A minimal set of tables and fields is given in figure 1.

<table>
<thead>
<tr>
<th>Table 1: Tracked Objects</th>
</tr>
</thead>
<tbody>
<tr>
<td>serial_id</td>
</tr>
<tr>
<td>integer</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2: Readers</th>
</tr>
</thead>
<tbody>
<tr>
<td>id</td>
</tr>
<tr>
<td>integer</td>
</tr>
</tbody>
</table>

*Figure 1: Minimal database configuration.*
The coordinates of the readers are assumed to be fixed most of the time, and should be entered ahead of time. In order to do this, an arbitrary point will have to be chosen as the origin, and the locations of the readers relative to the origin must be measured with a high degree of accuracy and precision. Conversely, the information in the Tracked Objects table is entirely dynamic. Objects can drop in and out of the table at will and their position data is assumed to be changing continuously. The timestamp field is used to record the time of the most recent signal received from the corresponding RFID. If it has been a long time since the last signal was received, the system might assume that the RFID has wandered outside of tracking range or that it is malfunctioning, and alert a human supervisor or take other appropriate action.

Note that, in order for the system to compute movement actions for the tracked objects (if desired), the system will need sufficient knowledge of the local topography; that is, a map. The system as described contains no facility for producing a map, so it is assumed that this data already exists in the system beforehand.

5. Client Application

The central system continuously receives the travel distance to each RFID from each reader. As long as there are at least three readers, this information can be used to calculate the three-dimensional coordinates of each RFID, which are then stored in the database. This calculation is performed based on time difference of arrival; that is, the difference in time it takes an RFID's signal to reach each of the readers, using the technique of multilateration.
Multilateration works as follows. If a single sensor knows the distance to a tracked object—but no other information—it can project a sphere outward from itself, and it knows that the object must lie somewhere on the surface of this sphere. This is true for every sensor that receives a signal from the tracked object. The intersection of two such spheres creates a two-dimensional circle, and it is known that the tracked object must lie somewhere on the circumference of the circle. If a third sphere is added, it will intersect with the other two spheres at exactly one point, which is the precise location of the tracked object. See figure 2 for a visual illustration of this principle.

![Illustration of determining location from time difference of arrival using multilateration.](image)

In practice, the intersections of the calculated spheres will not work out with this much precision, due to small errors resulting from manufacturing flaws and environmental factors. Therefore, only an approximate location can be derived, and the
computation becomes more complex. The accuracy of this approximation can be increased by adding more sensors.

Additionally, the computation for approximating the tracked object's position can be aided by various techniques. One such technique is a Kalman filter. The Kalman filter is an algorithm that operates recursively on noisy measurements to produce a statistically optimal estimate of the true state. In normal Kalman filtering, the state transition and observation models are linear functions, but there also exists an extension to Kalman filtering which enables its use on nonlinear systems. Extended Kalman filtering could be used to provide more accurate estimations of each tracked object's position given noisy input data.

6. Graphical User Interface (GUI)

The database is connected to a terminal which runs a graphical application that displays a map of the tracked space and the locations of all tracked objects within it. The map updates in real-time by querying the database with the latest position data. In addition to simply displaying a map, the GUI also allows the human operator to perform the following actions, all of which update the database:

- Delete serial numbers to remove tracked objects.
- Add serial numbers of new objects to track.
- Add or remove readers.
- Update the coordinates of preexisting readers.
The graphical portion of the application would likely be written using a high-performance graphics library such as OpenGL. The other features would automatically construct SQL queries which would then be forwarded to the database in order to update it with the new data.

7. Conclusions

Autonomous mobile robots typically use sophisticated sensor systems to determine their position, such as lidar. Quality lidar systems can easily cost several thousand dollars. Conversely, the tracking solution presented here requires only active RFID tags, enough readers to cover the space to be tracked, a system to house the central database and processor, and a terminal. The cost savings resulting from the use of the RFID system would grow in proportion to the number of robots to be tracked. For example, assume that a system uses 10 robots, each equipped with a $3000 lidar system, for a total cost of $30,000 for the tracking equipment. Assume that this can be replaced with ten $100 active RFID tags (with extra batteries for improved range), ten $100 inertial measurement units (for orientation tracking), three $2000 readers, a $5000 central system, and a $2000 terminal, for a total cost of $15,000. Under these assumptions, the RFID tracking equipment is half the cost of the lidar systems while providing comparable performance.

Note, however, that this system is only valid if accuracy within 10 cm is acceptable. If higher precision is required, then the proposed RFID system would be
unsuitable, because gaining higher precision would require clocking the readers to unrealistically high levels. Thus, for systems which require sub-centimeter accuracy (such as a virtual reality tracker), a tracker with finer granularity would be necessary.
References

