Localization Based on Ranges for Indoor Large-Scale Systems

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Abstract

The main objective of this thesis was to create a positioning system based only on range information for indoor environment with three elements, specifically acoustic signals, Bluetooth and Ultra-Wide Band (UWB). As for acoustic signals, the method for obtaining range information was the Time of Arrival (TOA) with triggering by a radio frequency signal from an Xbee module (with Zigbee protocol). In Bluetooth technology, these ranges were obtained from the power of received signal strength indicator (RSSI). And finally, using the method of Time of Flight (ToF) information relating to range was obtained from UWB signals. This paper presents the methods, concepts and technology that have a direct relationship with the development of this positioning system. Implemented solutions are described in order to meet the objective of this thesis and the behavior and performance of the positioning system were also evaluated.

Keywords: localization, wireless sensor network, range, ultrasound, Bluetooth, Ultra-Wide Band.

1. Introduction

Since ancient times, localization has been invaluable to humans in navigation on land, sea and air. In the twentieth century, advances in electronics and telecommunications enabled technologies such as GPS (Global Positioning System). The information from the location in free space enables diverse applications, such as vehicle location, location of people, resource discovery and games [1].

While the applications of localization mentioned before are common today in outdoor environments, and widely used due to the availability of GPS, applications for indoor can benefit greatly with location information. Nowadays indoor location is highly desirable for industrial technology, health and public safety. It’s known, there are several scenarios where GPS is not available, such as indoors or aquatic environments. To counter this problem in these scenarios, alternative systems based on distances, angles and signal strengths are applied.

In localization systems there is usually a node that needs its position, and a set of anchors / beacons that know their position a priori. Furthermore, in cooperative scenarios, different nodes have access to different information about the location and will interact to estimate their positions together in a more precise and flexible way than if they did individually.

Most of the proposed indoor localization systems only use one type of measure. In this thesis 3 methods will be used to obtain an indoor localization system that uses measurements of distances between nodes and anchors to find the position of the nodes. This localization system is based on a wireless sensor network that is composed of devices with capability to estimate, with 3 different methods, the position of a node: Acoustic signals, received signal strength indicator (RSSI) from Bluetooth technology and Ultra-Wide Band signals.

2. Localization in Wireless Sensor Networks

In outdoor localization, the most popular system is GPS. This system measure the distances between the user and a set of satellites, finding the location of the user anywhere on the globe. The main disadvantage of the GPS system is the need for line of sight between the satellites and the terrestrial receiver due to the high frequency used in this system, approximately 1.5 GHz, making it especially sensitive to obstructions caused by high vegetation or buildings which can completely block the signal or create the phenomenon of multi-path [1].

The approach for indoor positioning systems is similar to GPS because in an indoor environment, instead of satellites, anchors are deployed (typically on the ceiling) to provide support to the nodes of the wireless sensor network that attempt to discover their location. In this case at least 3 anchors for
localization in two dimensions (2D) and 4 anchors for three dimensions (3D).

The elements of the wireless sensor network created in this thesis will use three methods to calculate the distances between them, and use this data to discover the location of the nodes. The three methods used to find the distances between the elements will be based on the flight times of acoustic signals, the received signal strength indicator (RSSI) from Bluetooth technology and flight times of Ultra-Wide Band (UWB) signals.

2.1. Single-Source Localization

The created system will only work in the single-source localization context, i.e., the problem of locating a node through only distance values between the nodes and anchors that form the network, where only the anchors know their location a priori. In the context of single-source localization there is only communication between anchors and nodes and never between pairs of nodes, then only the distances between anchors-nodes are calculated and subsequently the location of each node is computed separately, independent of the other nodes on the network.

2.2. Acoustic Signals

Localization via acoustic signals is the most used technique in indoor localization because it is much more precise than localization with signal strength (RSSI) [2]. The disadvantage is that this method is more expensive and less accessible. In this thesis, distance measurements is the only technique used and the method to compute this distances is the Time of Arrival (ToA) with radio triggering.

To illustrate ToA with radio triggering, let’s suppose there are two nodes, called A and B, where one node wants to find the distance between them using acoustic signals. Each node is equipped with a microphone, speaker and an RF transmitter and receiver. As the nodes, clocks usually are not synchronized, they cannot calculate the distance between them by using acoustic signals. If node A sends an RF signal with an acoustic signal and node B receives this RF signal almost instantly, node B knows the time that the acoustic signal left node A. With this information, node B can compute the distance to node A with (1).

\[ d = (t_{\text{sound}} - t_{\text{radio}} - t_{\text{delay}}) \times (s_{\text{radio}} - s_{\text{sound}}) \] (1)

As illustrated in figure 1, the RF signal is first transmitted by node A, then waits a fixed time \( t_{\text{delay}} \) and then the acoustic signal is transmitted by the speaker.

The time when node B receives the RF signal is saved, \( t_{\text{sound}} \), and the microphone is enabled, so it can detect the acoustic signal from node A. The time when the microphone receives the acoustic signal is saved, \( t_{\text{sound}} \). With \( t_{\text{delay}}, t_{\text{radio}} \) and \( t_{\text{sound}} \), node B can calculate the distance to node A using (1). In this thesis, XBee modules based on ZigBee technology are used for radio triggering.

![Figure 1: TOA with triggering signal made by a radio signal.](image)

2.3. RSSI from Bluetooth Technology

Bluetooth technology can be used by localization systems using received signal strength indicator (RSSI) and received power level. Among Bluetooth Protocol layers, the ones that are relevant for getting the RSSI value, used to compute the distance between Bluetooth devices are:

- **Link Manager** — Can record the RSSI value of each received packet;
- **HCI** — Provides an interface where the link layer manager can be accessed and read the RSSI values through specific commands.
- **RFCOM** — To obtain RSSI values, packets are exchanged between devices using RFCOM.

It is possible to obtain the value of RSSI of each data packet that is received by the device within an established connection, having control over the type of packets and sampling rate. The RSSI value from an established connection through the HCI layer of the Bluetooth protocol, is taken into account as a parameter to the power level of reception \( (P_{rx}) \) or power control and not to estimate distances. It is necessary to convert the RSSI value to the receiving power level \( (P_{rx}) \). Considering 0 and -30 dBm values for the upper limit \((GRPR^+\)) and lower \((GRPR^-\)) respectively, it is possible to convert the RSSI value to Prx by equations (2), (3) and (4).

\[ PR_{x dBm} = RSSI_{dBm} + GRPR_{dBm}^+, \quad RSSI_{dBm} > 0 \] (2)
\[ PR_{x dBm} = RSSI_{dBm} + GRPR_{dBm}^-, \quad RSSI_{dBm} < 0 \] (3)
\[ GRPR_{dBm}^+, GRPR_{dBm}^- = PR_{x dBm} \] (4)

2.4. Ultra-Wide Band Signals

Ultra-Wide Band is a technology for data transmission that uses techniques that spread the energy of electromagnetic waves in a very wide frequency band, with a very low spectral power density. This low spectral power density limits potential interference with conventional radio systems and the high-bandwidth allows both very high data transfer rates.
as well as high precision tracking devices. These characteristics provide UWB signals resistance to multipath that conventional radio systems do not possess.

In this thesis, distances between anchors and nodes are obtained through a serial communication port in the network nodes. The Time of Flight (ToF) method is used by these devices to get this values of distances.

3. Developed System

This section describes the hardware and software that was developed in the scope of this thesis for the localization system.

3.1. Hardware

Hardware interactions between the components of the developed system in this thesis are illustrated in figure 2 with a simplified diagram. The following components were used:

- **UDOO Quad**;
- **XL-Maxsonar EZ0**;
- **Arduino Xbee Shield by rhydoLABZ**;
- **XBee 1mW Trace Antenna - Series 1**;
- **Plugable USB Bluetooth 4.0**;
- **UWB Kio ranging system**.

![Figure 2: Simplified diagram of the connections between all components.](image)

3.2. Network Elements

This section presents the main changes made to all the hardware to function as intended. The first issue was integration of the XBee shield on the UDOO. In the way the XBee shield comes originally, when it is placed on UDOO, the operating system and other components that depend on it freeze. This is due to the fact that the operating voltage of the UDOO is 3.3 Volts, while originally the XBee shield operates at 5 Volts. Therefore, it is necessary to change the XBee shield operating voltage to 3.3 Volts. To change the operating voltage it is necessary to remove the solder from 5 Volts and put it in 3.3 Volts.

With the change of the voltage to 3.3 Volts, even with these three components (UDOO, Xbee shield and XBee module) properly placed, there is an incompatibility in the internal links of UDOO with any external component that needs the pins TX0/RX0 for communication. In the original internal links of UDOO, available in the official UDOO documentation [4], communication between the two processors, iMX6 and SAM3X, is made through an internal UART serial link. This UART serial connection is always on and it is possible to upload developed programs in iMX6 to the SAM3X through it. But it is possible to conclude that this connection blocks the communication pins TX0/RX0 to any external component that needs these pins to transmit or receive data. The solution to this problem is to change the UDOO kernel in order to close this internal UART serial link (responsible for the communication between the two processors), freeing TX0/RX0 pins and create an alternative way to enable communication between the two processors again. The alternative way consisted in enabling a new internal UART to default pins 53/47 of UDOO (UART3) and, using another serial port in the SAM3X with the default pins 14/15 (Serial3). Through external links between these pins (copper wire) the two processors can transmit and receive data from each other. Figure 3 illustrates the links in normal UDOO operating mode with all these changes.

In order to obtain the values of the distances between network elements from the UWB devices a serial connection with modem support via USB is required. Again, it is necessary to slightly modify the UDOO kernel to give its USB ports modem support.

In this thesis XL-Maxsonars are used to compute the distance between network elements through acoustic signals. The problem is that these components operate as a sonar, measuring the distance to an object by constantly sending a beep from the speaker and then, enabling the microphone to receive the echoes as the acoustic signal bounces on surrounding objects. Ideally, one would like to be able to turn on the microphone of the XL-Maxsonar at any moment. A problem appeared when some tests were made with the XL-Maxsonar on different network elements and distances between them greater than 35 cm. By measuring the distance, the value was always 35 cm when two XL-Maxsonar were separated by more than 35 cm (even with the radio triggering signal). An oscilloscope was necessary to observe the moment of time when signals were transmitted / received in the XL-Maxsonar and analyze the problem. To analyze the cause of
this problem two different elements of the wireless sensor network were placed at 1.42 m distance. By using the TOA signal with synchronization between the two XL-Maxsonar, 35 cm is the value obtained in the XL-Maxsonar responsible for measuring the distance between them. The expected value is actually 71 cm because the XL-Maxsonar operates like a sonar, sending a signal and expecting the return signal, i.e. two flight times, while in this thesis two XL-Maxsonar are used simultaneously where one of them sends and the other one receives, i.e., only one flight time. Analyzing the pins of the XL-Maxsonar where the acoustic signal is received, figure 4, the yellow arrows corresponds to the signal that the Anchor XL-Maxsonar recognizes as the measuring distance, the blue arrows correspond to the signal that the Node should recognize as the measuring distance, the arrows in red are what effectively the Node XL-Maxsonar recognize as the distance (due to echoes created by the anchor), and finally the white arrows correspond to the amount of delay that must be corrected. To correct this delay, the program that the central Node runs on Arduino was modified to send the RF signaling signal, wait for 12 ms and then enable the XL-Maxsonar.

3.3. Software

In terms of software six distinct programs were created. In this system, there are three types of network elements: Central Anchor, Anchors and Nodes. There can only be one central anchor in the network, while the amount of the remaining anchors and nodes may vary depending on how many the user wants. As already mentioned, all these network elements will use the UDOO platform that has two processors, i.MX6 and SAM3X8E. The three programs that need to run on i.MX6 were developed using Python and for the remaining three programs running on SAM3X8E, Arduino (C/C++) was used.

The main functions of the central anchor are to communicate to the other network elements its function in a given time and show the user all the data available related to the distances between network elements.

In the remaining anchors, their only function is to maintain a constant connection to the network nodes and activate the XL-Maxsonar in the moment that it receives indication of the central anchor.

The nodes function is to collect all the data related to the distances between them to all connected anchors in the three methods available (Bluetooth, UWB and XL-Maxsonar) and send all this information to the central anchor.

4. Experimental Results

This section presents the tests performed and the
results obtained with the developed system in this thesis.

4.1. Distance Measurements

Before carrying out the 2D and 3D location tests, in order to compute the position of a node, tests were performed individually for the three technologies to have an idea of the behavior and accuracy of the distance values that can be obtained between network elements. These preliminary tests consist only in deploying two network elements, initially spaced 50 cm apart, and gradually increasing the distance between them in linear intervals of 50 cm, until they reach 10 m, recording the average of 30 samples of distance values obtained by the three methods individually. These tests were done in a laboratory, with the two network elements always in line of sight and without nearby objects.

As mentioned earlier, the RSSI value from an established Bluetooth connection is taken into account as a parameter to the power level of reception \( P_{rx} \) or power control and not to estimate distances. It is necessary to convert the RSSI value obtained to the receiving power level \( P_{rx} \) using equations (2), (3) and (4). To associate the \( P_{rx} \) value with the corresponding distance a linear calibration curve (equation 5) was obtained, from the test already described above, which represents the behavior of the RSSI values of Bluetooth technology indoors.

\[
\frac{d}{\text{m}} = \frac{-P_{rx}(\text{dBm}) + 32.432}{0.3365} + 32
\]  

For the acquisition of distances between network elements via acoustic signals the XL-Maxsonar is used, as mentioned before. The distance calculation using this method is always made on the nodes of the network, using a digital PWM pin of Arduino to receive the PWM signal from XL-Maxsonar pin 2. The PWM signal received is the time at which the acoustic signal was sent \( t^+ \) and the time at which an acoustic signal is received \( t^- \) within a XL-Maxsonar read cycle (99ms). With these times, it is possible to compute the distance represented in the PWM signal with equation (6), which converts the time to the distance in centimeters assuming the time obtained from the PWM signal represents the time that the acoustic signal is sent from the node \( t^+ \) and the time the acoustic signal is received from the anchor \( t^- \).

\[
d = \frac{(t^- - t^+)}{147} \times 2
\]

As for the distance values obtained with Ultra-Wide Band technology, these are again obtained in the node via a USB serial connection. It is only necessary to know the relevant port, typically found in ‘/dev/ttyUSB0’ and the data transmission rate (band rate), in this case 230400 bits/s.

To compare the error \((d_{\text{computed}} - d_{\text{real}})\) of the distance values obtained by the three methods, the data collected from the individual tests are represented in figure 6.

![Figure 6: Error comparison between the 3 methods.](image_url)

As expected the calculation of the distance via RSSI Bluetooth technology is the method that has more randomness and error when compared with other methods. This error is mainly generated by the multipath caused by local features in which the tests were conducted (closed environment). Part of the error is also due to the interference caused by technologies used in the test lab as WiFi, which operates in the same frequency band (2.4 GHz).

In the case of XL-Maxsonar, the maximum error recorded in this test was 2 meters when it reached the maximum range (approximately 8 meters) with the error steadily increasing with distance. Exceeding the maximum range, the XL-Maxsonar begins to output erroneous measurements. Lastly, the distance values obtained by the UWB technology are the most consistent with a maximum error of 0.1 meters.

4.2. Localization Algorithms

After obtaining the distance between network elements with the three methods, it is necessary to present the estimated position of the network nodes based on the known positions of the anchors. In this thesis only distance values in the single-source location context were used. The problem addressed is the localization of a node via distance values only between nodes and anchors which constitute the network, where only the anchors know their position. After acquiring range measurements, a localization algorithm is required to compute the relative estimated position of the node.

For the 2D location test SLCP (Source Localization in the Complex Plane) and SR-LS (Least-Ranged Least Squares) were used, where the first (7) is more accurate but slower to compute and the second (8) is faster to compute but more sensitive
to noise [5,6,7]. The location algorithms used in the 3D test were SLNN (Source Localization with Nuclear Norm), equivalent to SLCP but for 3D location, and SR-LS again.

\[
\min_{x} \sum_{i=1}^{m} (||x - a_i|| - d_i)^2 \quad (7)
\]

\[
\min_{x} \sum_{i=1}^{m} (||x - a_i||^2 - d_i^2)^2 \quad (8)
\]

4.3. 2D Localization

In this test, as already mentioned, the goal is to get the position of a node in 2D. Similarly to the preliminary tests described in section 4.1, a node was placed in a certain position within the area of the laboratory used for this test. Then an anchor was placed at 12 positions randomly across the test area, calculating the distance between the anchor and the node through the three possible methods (Bluetooth, XL-Maxsonar and UWB) for each position of the anchor. By using equation (5) for Bluetooth, and equation (6) for the XL-Maxsonar, the distance between the anchor and the node in the 12 different positions was calculated. In this test, as in preliminary tests, the average of 30 samples of distance values obtained by the tree methods individually was recorded for each position.

When computing the error \(d_{\text{estimated}} - d_{\text{real}}\) of each method individually, the graph of figure 7 is obtained. As expected, Bluetooth has the highest error margin. With the randomness and the amount of high error observed with this method it is possible to conclude that for the indoor localization system created in this thesis the location based on RSSI values obtained using Bluetooth technology does not work. Similar localization systems to the one developed in this thesis also have significant problems with location with Bluetooth technology [3]. On the contrary, methods that use XL-Maxsonar or UWB have an acceptable error. In the case of XL-Maxsonar, it is possible to notice the same trend observed in preliminary tests, with error steadily increasing with distance.

With only three UDOOs available, it is only possible that two anchors (1 and 3) have one, and the last one used in conjunction with a Cricket listener, forming the node of this network. Anchors 1 and 3 are able to obtain the distance between themselves and the node via four different methods (Bluetooth, XL-Maxsonar, Cricket and UWB), while anchor 4 has only two methods (UWB and Cricket). Finally anchors 2 and 5 only have the Cricket to obtain distance values.

At each position the distances were recorded between the 5 anchors and the node, with all available methods. The results were split into 4 parts and the SLNN and SR-LS algorithms were run with the data of each part. The results were divided as follows:

- In the 1st part only the distance values acquired by the Cricket system for the 5 anchors are used;
- In the 2nd part only values from the Cricket system and the XL-Maxsonar (in the anchors incorporating an UDOO) are used;

<table>
<thead>
<tr>
<th>Real position of the node</th>
<th>x(m)</th>
<th>y(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLCP - XL-Maxsonar</td>
<td>2.7322</td>
<td>1.0345</td>
</tr>
<tr>
<td>SR-LS - XL-Maxsonar</td>
<td>2.7796</td>
<td>1.2901</td>
</tr>
<tr>
<td>SLCP - UWB</td>
<td>2.8607</td>
<td>1.0713</td>
</tr>
<tr>
<td>SR-LS - UWB</td>
<td>2.9027</td>
<td>1.0767</td>
</tr>
</tbody>
</table>

Table 1: Estimated node position.
• In the 3rd part only values from the Cricket system and from 2 UWB (in the anchors incorporating an UDOO) are used;
• Unlike Bluetooth and XL-Maxsonar, UWB doesn’t need a UDOO to record the distance between the anchor and the node. By having a third UWB device available, it was put together with a Cricket beacon forming anchor 4. Therefore, in the 4th part the values of the Cricket system and UWB were used again, but with this change in anchor 4.

Bluetooth values were also obtained, but like the 2D test, with the randomness and large amount of error observed, it was again possible to conclude that using RSSI values obtained with Bluetooth technology, location in indoor environment doesn’t work for this localization system.

**Table 2: RMS and STD of the 8 tests.**

<table>
<thead>
<tr>
<th>Number of the test</th>
<th>Description</th>
<th>RMSE (m)</th>
<th>Standard Deviation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SLNN Cricket</td>
<td>0.6072</td>
<td>0.2542</td>
</tr>
<tr>
<td>2</td>
<td>SLNN Cricket + XL-Maxsonar</td>
<td>1.2291</td>
<td>0.5603</td>
</tr>
<tr>
<td>3</td>
<td>SLNN Cricket + 2 UWB</td>
<td>0.954</td>
<td>0.2747</td>
</tr>
<tr>
<td>4</td>
<td>SLNN Cricket + 3 UWB</td>
<td>1.2294</td>
<td>0.5143</td>
</tr>
<tr>
<td>5</td>
<td>SRLS Cricket</td>
<td>0.5034</td>
<td>0.3003</td>
</tr>
<tr>
<td>6</td>
<td>SRLS Cricket + XL-Maxsonar</td>
<td>1.2544</td>
<td>0.5903</td>
</tr>
<tr>
<td>7</td>
<td>SRLS Cricket + 2 UWB</td>
<td>0.8143</td>
<td>0.3003</td>
</tr>
<tr>
<td>8</td>
<td>SRLS Cricket + 3 UWB</td>
<td>1.47</td>
<td>0.9276</td>
</tr>
</tbody>
</table>

As shown by the graph of figure 9, the results corresponding to the Cricket system (part 1), with both the SLNN and SR-LS location algorithms, were the most accurate when compared with the rest of the results. The results corresponding to Crickets + 2 UWB (part 3) were the second more accurate and the results from Crickets + XL-Maxsonar (part 2) were the less accurate, as expected. On the other hand, the results of the Crickets + 3 UWB (part 4) show values with less accuracy than expected, particularly with the SR-LS algorithm. The Standard Deviation in this case is also significantly higher when compared to the other results.

Analyzing the results, both for SLNN and SR-LS, an offset in the estimated node positions can be observed in the x and y axis to the right and up relative to the actual positions of the node. This mismatch occurs in the 1st part of this test, corresponding only to the Cricket system, and they persist in other parts as they all rely on Cricket measurements to some extent. This mismatch can be observed in figure 8, that corresponds to the 1st part of this tests with the SR-LS, where the blue points and lines represent the real node positions and route, and the red points and lines represent the estimated positions and route for the node.

The Root-Mean-Square Error (RMSE) with equation 9 and the Standard Deviation with equation 10 were used to compare the accuracy between each part of the results with the two location algorithms.

\[ RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} |x_i - \hat{x}_i|^2} \]  
(9)

\[ \sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (||x_i - \hat{x}_i|| - RMSE)^2} \]  
(10)
Figure 10: Error analysis on z coordinate of SR-LS.

dinate increases considerably both the RMSE and
the Standard Deviation, affecting the results of the
Cricket + 3 UWB. Anchor 5 was placed 30 cm
below the rest of the anchors to break up the near-
planar configuration and associated estimation am-
biguities, but it appears that it may not be enough,
as some of the algorithms still lead to excessive error
in the z coordinate in some instances.

5. Conclusions and Future Work
In this thesis a localization system for indoor en-
vironments was created, based on a wireless sensor
network in the context of single-source location and
based on distance values. In this localization sys-
tem, distances between network elements are cal-
culated through the use of acoustic flight times,
received signal strength indicator (RSSI) by Blue-
tooth technology and Ultra-Wide Band signals. A
set of conditions and tests were presented, with the
intention of observing if the operation of the local-
ization system created corresponds to the objectives
outlined in this thesis and compare the accuracy of
the three methods used. With these tests it was
concluded that, in the current version of the local-
ization system created, the calculation of distances
between network elements with RSSI values of Blue-
tooth technology is not feasible for indoor environ-
ments due to the randomness and high degree of er-
or observed, mainly because of multipath effects.
As for the acoustic flight times method, used by
the XL-Maxsonar, the error in the measured dis-
tances increases with distance and is necessary that
the network elements with the XL-Maxsonar stay
within the angle of coverage of each XL-Maxsonar
transducer. As expected the most accurate method,
within these 3, are the UWB signals. Even though
surpassing both Bluetooth and XL-Maxsonar, the
calculation of distances between network elements
through UWB signals does not have a better accu-
ry than the Cricket system, as seen in the tests
performed in this thesis.

As only 3 UDOOs were available, it was not pos-
sible to perform all the foreseen tests, limiting the
network to only two anchors and a node. At least
3 anchors for 2D location and 4 anchors for 3D
location are needed. In this thesis it was necessary
to resort to an existing set-up, consisting of a
Cricket system due to this problem. By acquir-
ing more components to create more network ele-
ments it is possible to test 2D and 3D localization
with this system only. Adding more XL-Maxsonar
to each network element is also beneficial for the
distance calculation. Also on the acoustic part
of the system, the synchronization method of the net-
work elements to calculate the distances through
XL-Maxsonar can be improved. Finally, adapting
the system created in this thesis to the collabora-
tive localization scenario is an added value, making
it more flexible and giving it a wider range of dis-
tance values between network elements, providing
this data to collaborative location algorithms.

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