Cooperative Indoor Localization with Ranging and Orientation Data

C. C. Chang*, G. W. Lee, and T. Y. Lee

Department of Applied Geomatics, Chien Hsin University of Science and Technology

ABSTRACT

The simplification of devices and procedures are crucial factors for consideration in achieving indoor localization. This study used a combination of ranging and orientation devices to develop and test a localization method with a cooperative operation of multiple mobile terminals. The multiple mobile stations are cooperatively organised into a linear model to obtain the range and orientation between each device. Subsequently, the dead reckoning method is adopted to obtain the localization coordinates of each device based on the known coordinates of an outdoor reference point. This study conducted localization testing on a multipoint line approximately 100 m long and obtained a 2D root mean square (RMS) error of around 6.1 m. Furthermore, if another reference point is also established at the end of the measured line to assist in localization, the coordinate closure obtained can substantially reduce the RMS error by up to 79%, or 1.2 m after correction. The characteristics of this method are suitable for localization use in emergencies (such as fire fighting) or the monitoring of automated factory vehicles.

Keywords: indoor localization, cooperative operation, ranging, orientation

運用距離及方位感測之協同式室內定位技術

張嘉強*　黎驥文　李姿瑩

健行科技大學應用空間資訊系

摘　　要

使用裝置及操作程序的簡單化，將會是室內定位的重要考量因素。本研究嘗試利用距離及方位感測裝置之組合，發展並測試一種由多點協同運作之定位方法。在由多點所組成線狀方式之協同定位模式下，藉由室外起始點之已知坐標，在取得各裝置間的距離及方位感測量之後，即可配合航位推算模式，取得知各裝置點之定位坐標成果。本研究在針對一條約 100 公尺長度之多點進行定位測試後，所獲得之平面誤差 RMS 值約為 6.1 m；但如可在測線結尾處輔以另一參考點，則透過坐標閉合差之取得，可逐點進行配賦修正，此時之 RMS 誤差將可降低 79%，大幅改善至 1.2 公尺。此技術之運作特性可適合做為緊急事件（如火場救援）或工廠自動化車輛監控所需之定位使用。

關鍵詞：室內定位，協同式作業，測距，方位

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Ⅰ. INTRODUCTION

Because of the rapid development of mobile computing devices, both professionals and general public have exhibited increasing demand for ways to obtain real-time locations and determine mobile pathing. In the past few years, several location awareness systems have been developed, with the Global Navigation Satellite System (GNSS) being the most widely used. As we know, the GNSS is a positioning system based on satellites. The basic principle of the system is the reception of observed signals from more than four satellites at a specific site to facilitate positioning. However, the main operational deficiency of the GNSS system is the interruption of direct signal transmission between satellites and receivers caused by physical objects between them. As such, localization performance in indoor and sheltered outdoor areas still needs to be improved or expanded.

To fulfil mobile localization demands in areas where GNSS reception is difficult to achieve, numerous indoor localization proposals have been developed. Such technology to be generated is based on its high commercial value and wide applicable places including transportation hubs (such as airports and train stations), large-scale buildings (such as school campuses, hospitals, or exhibition venues), and commercial spaces (such as shopping centers and office buildings). Its wide range of services includes applications in personal navigation, social networking, emergency rescue, security, logistics, and factory automation. The total industry value is projected to increase considerably from 450 million USD in 2013 to 2.6 billion USD in 2018 [1].

The precision achievable by using localization methods is the primary factor driving the development of technology and its applications. In the domain of mobile localization, a precision of lower than 11 m is referred to as low precision, 6-10 m is referred to as medium precision, and 1-5 m is referred to as high precision. High precision solutions are generally associated with higher costs and higher infrastructure requirements. According to the results of a worldwide industry survey, up to 40% of respondents indicated that a precision between 3 and 10 m is sufficient to meet the demands of indoor localization. However, 35% of respondents indicated that a precision between 1 and 3 m is necessary to meet those same demands. In sum, meeting precision requirements equivalent to those of GNSS navigation is the goal for indoor localization industry [2].

In the past several years, technologies used by indoor localization have included WiFi, ultra-wideband (UWB), cellular signalling, television signals, bluetooth, lasers, step detection, map matching, geomagnetic matching, and GNSS shadow matching etc. [3]. Of these, in large-scale indoor environments with an existing Internet infrastructure, the simplest localization method is WiFi triangulation [4][5]. Although the operational costs of this method are acceptable, its precision and availability remain insufficient for numerous applications. As such, this method is often combined and expanded upon with other methods, such as WiFi fingerprint, proximity, Bluetooth beacon, or the Indoor Messaging System (IMES) to achieve more diverse indoor localization methods [6][7].

The development of feasible indoor localization technologies, whether for WiFi or bluetooth beacon localization, require infrastructure installation, reference point coordinate measuring, and wireless signal calibration in indoor environments beforehand; however, these requirements are difficult to implement for certain spaces. As such, how feasible sensing devices, auxiliary information, and spatial algorithms can be used to develop a precise and innovative indoor localization method featuring quick and easy operations was the primary motivation of this study.

The indoor localization method examined by this study uses a minimal amount of reference points and applies the range and orientation data detected by each mobile device in conjunction with basic navigation and surveying algorithms to construct a simple cooperative indoor localization method. When in operation, this method does not require the placement of numerous signal sources in advance and is suitable for emergency rescue, military searching or automatic tracking, and therefore possesses substantial potential for practical applications.

Ⅱ.LOCALIZATION METHOD AND OPERATING PROCEDURES

The indoor localization method proposed by this study is based on the localization demands of multiple mobile terminals, and thus requires the connection of multiple mobile devices followed by range and orientation sensing to establish the geometric relationship between each mobile station for localization. As such, it refers to this method as cooperative localization. This localization method generally requires an outdoor starting reference point with known coordinates and the use of rangefinder and electronic compass devices to determine the range and orientation between each device, as well as the transmission of sensing data to the monitoring terminal to confirm the coordinates of each mobile station.

The primary operational framework of the localization method outlined in this study is shown in Fig. 1. For it, when the area requiring indoor localization cannot effectively receive GNSS satellite signals, Network Real Time Kinematic (NRTK) positioning can be applied in open outdoor spaces to quickly and precisely obtain the beginning and end reference points on a centimetre level and establish the coordinate control system of this localization line. Dead reckoning algorithm can then be used in conjunction with the range and orientation data between each mobile station to calculate the spatial coordinates at the monitoring terminal. If the mobile station at the front can also connect with the ending side of reference point, the coordinate closure can be obtained to adjust the calculated coordinate and thus reduce the error for each mobile station. After the adjusted coordinates are obtained, moving trajectories of the mobile stations can be realised at the monitoring terminal, and localization data can be also transmitted to each mobile device.

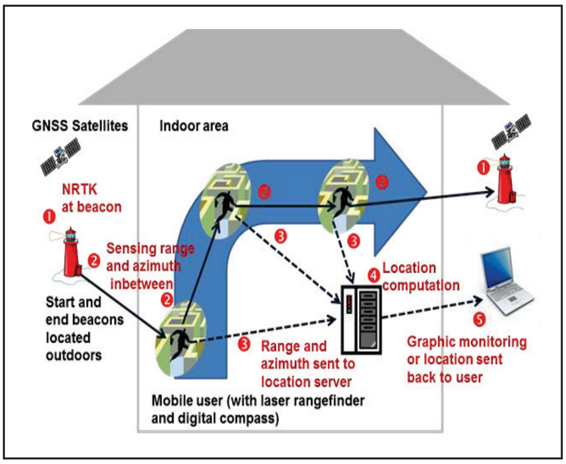

Fig. 1 Operational framework of the cooperative localization method

To determine mobile stations' plane coordinates, this cooperative localization method starts with the known coordinates (N_S, E_S) of a reference point and the measurement of the orientation (α) and the distance (S) between the reference point and the first mobile station to calculate the coordinate increments (ΔN, ΔE) and the coordinates (N_M, E_M) of the mobile station. The coordinates of the subsequent mobile stations can be sequentially calculated with the dead reckoning algorithm shown as follows:

$$E_M = E_S + \Delta E = E_S + S\sin\alpha$$
$$N_M = N_S + \Delta N = N_S + S\cos\alpha \qquad (1)$$

Ⅲ. LOCALIZATION TESTING AND DATA ANALYSIS

3.1 Sensing Equipment and Error Estimation

The cooperative localization method proposed by this study uses an engineering-purpose handheld laser rangefinder and a smartphone App with geomagnetic sensing functions as the primary measurement tools. When the method was tested, the laser rangefinder was operated in conjunction with reflective paper targets to have an effective measurement distance of up to 50 m. Before evaluating the measurement precision, this study established a 30 m long baseline to determine that the ranging error was likely less than 2 cm by calibrating the standard distance and measured distance between the seven baseline points (Fig. 2).

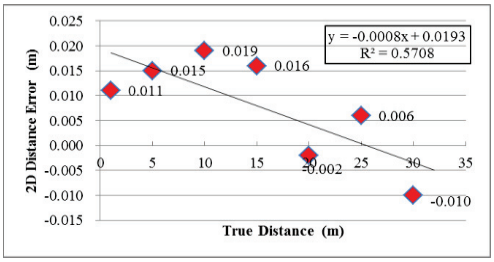

Fig. 2 Handheld laser rangefinder calibration error

For the operation process of the cooperative localization method, the error budgets include the coordinate error of the reference point measured by using NRTK (approximately 3-5 cm), the ranging error (approximately 2 cm), and the relatively larger error caused by orientation measuring. Orientation error typically has three causes: the orientation value provided by the smartphone App is only effectively measured in degrees, the orientation data detected by the App is based on the geomagnetic north rather than true north, and the orientation measurement does not work with precise targeting.

To understand the level of possible error caused by the smartphone App for orientation measurement, this study established another baseline with different angled sections to obtain the orientation calibration error by comparing the measurements with the standard orientation inversely calculated from any two baseline points' known coordinates. The testing results of five orientation angles for six baseline points are as shown in Tab. 1.

Tab. 1 Smartphone App orientation measurement error (unit: degrees)

Test Section	Standard Orientation	Measured Orientation	Error
1	115.776	121	5.224
2	36.754	42	5.246
3	112.793	118	5.207
4	41.926	47	5.074
5	43.789	49	5.211
RMS			5.193

The testing results indicate that the smartphone App orientation sensing error reached up to 5.2 degrees; error of this magnitude is equivalent to a maximum coordinate error of 2.7 m for 30 m distances and therefore requires particular attention.

3.2 Testing with One Starting Side Reference Point

This experiment was conducted at the athletic field of a university campus, simulated as an indoor space for only personal mobile devices applying but all with precise known coordinates at the test sites. The placement of the required initial reference point and other cooperative localization devices are shown in Fig. 3. The known values required by the localization testing process were the coordinates of the initial reference point, with the observed values being the measured range and orientation between the various adjacent devices. These values enabled dead reckoning to be used to calculate the coordinates for mobile station ①, followed by those for station ② and the other stations.

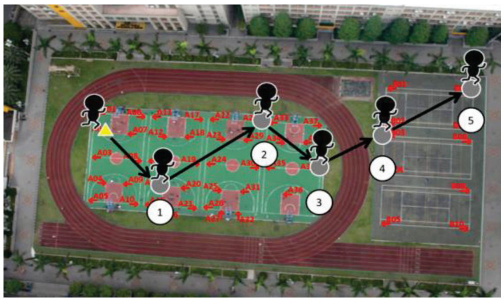

Fig. 3 Cooperative localizing testing performed by using the starting side reference point (yellow triangle as reference point)

Because this study primarily examines the feasibility of relevant localization methods, real-time data transmission was not considered. As such, the data calculation was carried out through post-processing. The precise coordinates of each device point were determined in advance by using NRTK. The differences between the calculated coordinates and the precise coordinates then can be used to obtain the overall RMS errors of the localization method. The localization coordinate errors are shown in Tab. 2.

Tab. 2 Cooperative localization errors from using one initial reference point

Site	Component		
	E (m)	N (m)	2D (m)
1	-0.86	-1.81	2.00
2	1.55	-3.67	3.98
3	0.83	-5.43	5.50
4	2.17	-6.60	6.95
5	3.96	-8.35	9.24
RMS	2.20	5.65	6.06

As shown in Tab. 2, the approximately 100 m test line formed from the five mobile stations resulted in two plane coordinate component errors greater than 2 m and an overall 2D RMS error of around 6.1 m. In addition, a gradual increase of localization error from 2.0 m to 9.2 m was found with the distance extension of the test line. It was caused by the continual accumulation of measurement errors (in particular orientation errors produced by the electronic compass) and the resulting expansion in localization errors for later mobile stations.

3.3 Testing with an Additional Ending Side Reference Point

Because the use of only starting side reference points for cooperative localization exhibits the characteristic of increasing localization error caused by the accumulation of measurement error, this study referenced the closure error of traverse surveying and added another reference point with known coordinates at the ending side of the test line, then carried on a distance-dependent correction for closure error. In conducting the localization test, this study changed the terminal point of the test line (point ⑤ in Fig. 3) into a reference point with known coordinates, and only conducted localization calculations and closure error correction on mobile stations ①-④.

Between the placement of a single reference point at the starting side or the placement of reference points at both the starting and ending sides of the test line, the latter exhibited superior localization control conditions because of the provision of the coordinate closure for this linear measurement. Furthermore, the coordinate correction enabled the calculation of corrected coordinates for each mobile station. The localization error of this test is shown in Tab. 3 and can be compared with the 2D localization error of Tab. 2 for the four points. The comparison is shown in Fig. 4.

Tab. 3 Cooperative localization errors from using starting and ending side reference points

Site	Component		
	E (m)	N (m)	2D (m)
1	-1.56	-0.33	1.60
2	-0.22	0.06	0.22
3	-1.61	-0.29	1.64
4	-0.91	-0.11	0.92
RMS	1.22	0.23	1.24

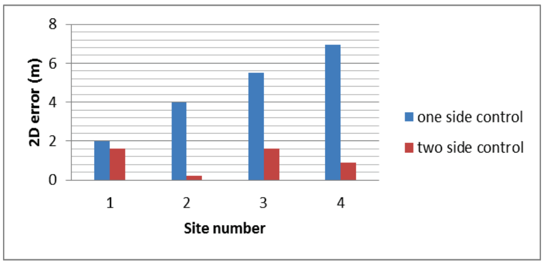

Fig. 4 Comparison of 2D localization error with two types of reference point usage

As shown in Tab. 3, the localization RMS error of the mobile stations were all lower than 1.5 m for both plane components, whereas the overall 2D localization error was approximately 1.2 m. In contrast to the results outlined in Tab. 2, which reflect the usage of a single starting side reference point without closure correction, the overall 2D localization error decreased from 6.1 m to 1.2 m with the introduction of the ending side reference point, indicating an improvement of 79%. Furthermore, the comparison of the 2D localization error of the two types of reference point usage illustrated in Fig. 4 revealed that the rising error (with increasing distance) associated with the usage of a single reference point was eliminated with the introduction of the ending side reference point as a linear control and a closure error correction; the localization error between each mobile station exhibited no substantial increase associated with distance.

3.4 Radiation Type Localization Testing

As illustrated by the aforementioned experiments, cooperative localization method employing geometric connections between mobile devices with the minimum number of reference points results in the gradual accumulation of error. Although the addition of an ending side reference point improves this difficulty, other solutions may be required when adding an additional reference points is not easy to accomplish. This study also examined the radiation type of localization, which is illustrated in Fig. 5. To test this method, a single reference point was established at the starting location, with ranging and orientation measurements directly conducted from the reference point to each mobile station (points ①-⑤). The known coordinates of the reference point were further used to calculate the anticipated coordinates of each mobile station. The resulting error of radiation localization is shown in Tab. 4.

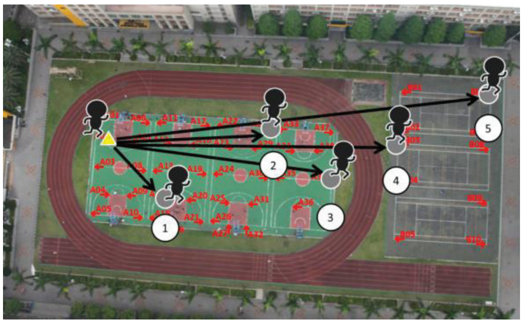

Fig. 5 Radiation type of localization test (yellow triangle as reference point)

Tab. 4 Radiation localization errors

Site	Component		
	E (m)	N (m)	2D (m)
1	-0.95	-1.75	1.99
2	1.41	-3.79	4.04
3	-1.11	5.40	5.51
4	1.86	-6.78	7.03
5	3.15	-7.47	8.11
RMS	1.87	5.45	5.76

As shown by the radiation localization results in Tab. 4, the mobile station 2D RMS error was approximately 5.8 m, in which a greater distance associated with a higher level of localization error (2.0-8.1 m). This phenomenon was primarily caused by the increase in radiation distance with higher range and orientation sensing errors. Furthermore, a comparison with the localization error illustrated in Tab. 2 demonstrated that the RMS error difference between cooperative and radiation methods both employing a single reference point was small (error difference of 0.3 m), with the radiation localization error exhibiting an approximately 5% improvement only.

IV. CONCLUSION AND SUGGESTIONS

The cooperative localization methods employing range and orientation sensing examined by this study require the following elements: the coordinate measurement of at least one initial reference point, ranging and orientation measurements between the reference point and subsequent mobile stations, and the establishment of the dead reckoning calculation algorithm. If the ending side of the measurement line formed by the mobile stations can be connected to another additional reference point, the coordinate closure error can be obtained for further localization correction.

The cooperative localization method proposed by this study can transmit spatial measurements to a monitoring terminal through the operation of multiple mobile stations to perform localization calculation and coordinate correction. Because the reference point and mobile stations are primarily on the same horizontal plane, this study was primarily conducted using 2D localization. From a practical perspective, if localization is limited to the use of a single reference point in a detectable range, the radiation type of localization method can be applied (testing accuracy of 5.8 m within 100 m). If the operational environment limits the detection range, then the cooperative localization method can be applied (testing accuracy of approximately 6.1 m). However, if the ending side mobile station can be connected with the other reference point, coordinate correction can be conducted to obtain the minimum localization error (testing accuracy of approximately 1.2 m), reaching an optimisation ratio of approximately 80%.

This study conducted data post-processing to verify the aforementioned methods. The operation of real-world systems requires the development of real-time sensing and calculation systems, and the resolution of concerns such as the calibration and integration of ranging (such as laser, infrared or BLE beacon etc.) and orientation sensors (such as gyro or declinometer etc.), transmission of real-time signal, and design of display platform. However, the localization methods provided by this study possess a potential applicable value in disaster rescue or automated factory environments.

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