Seamless Mobile Robot Localization Service Framework for Integrated Localization Systems

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Abstract—**According to the importance as one of the most basic preconditions for autonomy of mobile robots, efforts to provide global localization services continuously without loss have been advanced so far, and with current trends toward indoor service robots, not only outdoor but also indoor global localization is highly demanded. However, none of existing localization systems guarantees seamless and transparent global localization services regardless of indoor and outdoor. In this paper, we propose Integrated Localization Service Framework for mobile robots to address seamless global localization services. Our key considerations for the proposed framework are seamlessness by applying a new localization method and transparency by designing new architecture of fusion. We also implement Integrated Localization System by embodying the proposed framework based on RF technologies, and show that it achieves reasonable localization accuracy compared to other existing localization systems as addressing seamlessness and transparency.**

Keywords—**Framework, Localization, Seamless, Mobile Robot, Wireless Sensor Networks**

I. INTRODUCTION

Mobile robot localization is a process of determining and tracking the location of a mobile robot relative to its surrounding environment. It is one of the most basic preconditions for autonomy of mobile robots, like not only remote monitoring but also successful navigation.[1][2] Due to the importance of mobile robot localization, a number of methods and systems have been proposed and developed so far. However, traditional localization methods based on range sensors, computer vision are prone to fail especially in dynamic and crowded environment, and dead-reckoning methods which utilize when global localization is not available accumulate localization errors which may cause serious and critical problems.[3][4] Generally, localization in this category also accompanies high complexity of computation.[5]

Furthermore, despite current trends toward indoor service robots like security robots, cleaning robots, and home service robots lead high demanding for localization in both indoor and outdoor, still none of existing localization systems and protocols guarantees seamless global localization services regardless of indoor or outdoor, and previous integration works [6][7] also suffer loss of global localization services in the situations, handoff between different localization systems or transition between indoor and outdoor. Since lack of global localization may cause serious problems such as crash of mobile robots, or harm of people around, therefore a framework to provide seamless global localization, regardless of indoor and outdoor, is required.

Our contributions are summarized as following. First, we present abstract modeling of indoor and outdoor localization environment, called Global Localization Model. Based on the defined model, we design software framework for seamless integration, Integrated Localization Service Framework (I-LSF), with new fusion architecture and new localization method to remove loss of global localization services. Finally, we implement and evaluate Integrated Localization System which embodies the framework based on RF technologies like WPAN, WLAN and GNSS.

The rest of this paper is organized as follows. Section II describes the global localization model. Section III presents architecture and considerations of I-LSF. The design and implementation of Integrated Localization System is explained in section IV. Section V evaluates the performance of the system. Finally, section VI concludes this paper.

II. GLOBAL LOCALIZATION MODEL

In this section, we first define an abstract model of indoor and outdoor localization environment to describe components for localization services and infer requirements. As depicted in Figure 1, the environment contains many localization zones, Zone A, B, C, …, which consist of many cells inside. In each cell, localization infrastructure which uses various localization technologies, WPAN-based, WLAN-based, or GNSS-based, is installed for localization services. The installed infrastructure consists of 3 or 4 anchors which are embedded in surroundings and satellites in the outer space. Regardless of localization

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technologies used in the cell, mobile robots can get seamless and transparent global localization services on top of Integrated Localization Service Framework which we will propose in the next section.

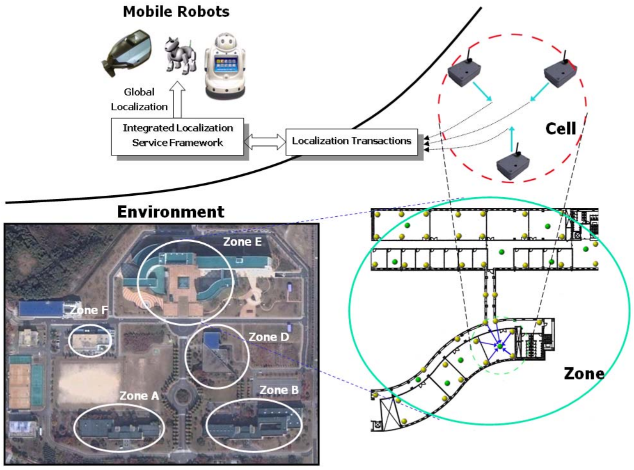
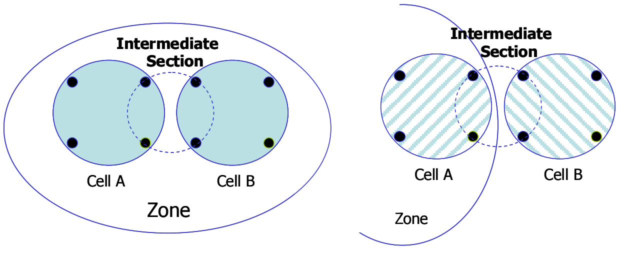


Figure 1. Global Localization Model

As briefly introduced, the model defines the following terminologies: Cell, Zone, and Intermediate Section. First, Cell is a basic unit of localization infrastructure. It is modeled as a circle which contains 3 or 4 homogeneous anchors whose location is already known. The anchors generate localization transactions, a series of transmissions for one measurement. Only one localization technology is able to employ in the cell. This model aims to describe anchor-based localization systems, but we assume satellite-based systems are also mapped into this model at a moment. Relations between independent cells are based on those between sets. They may be independent, overlapped, contain others, or be contained by others. Next, Zone is defined as a collection of adjacent cells which use a homogeneous localization technique. Single building may construct a zone. Consequently, several zones are constructed around a campus. Zone is modeled as a best-fit ellipse for all cells contained. Although the modeling of zone does not provide any practical influence in real system, this offers congregate views to handle a set of cells in place.



(a) Between Homogeneous Cells (b) Between Heterogeneous Cells

Figure 2. Definition of Cell, Zone and Intermediate Section

Lastly, we define Intermediate Section (IS) which is an important concept for seamlessness. As depicted in Figure 2, two remote cells are installed independently, and the region which consists of 4 anchors from different cells is formed between them. We call the region as Intermediate Section. In case of the former, depicted in Figure 2-(a), two cells are in the same zone and utilize the same localization technology. By definition of the cell, this intermediate section is also a valid cell. In case of the latter, depicted in Figure 2-(b), two cells are located in independent zones which utilize different localization technologies. The intermediate section here is constructed by combination of anchors which have different technologies.

III. I-LSF

The Integrated Localization Service Framework (I-LSF) is a software framework to offer seamless global localization services for mobile robots to utilize in their own purpose, by integrating multiple RF-based localization systems, regardless of whether their environment is indoor or outdoor. Figure 3 illustrates basic architecture of the framework.

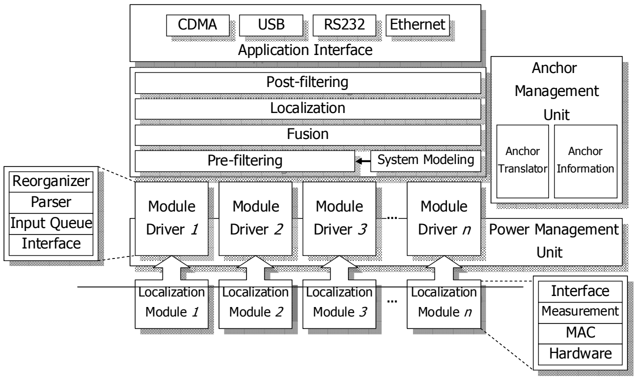


Figure 3. Basic Architecture of I-LSF

Localization Module part consists of 4 sub-layers: Hardware, MAC layer, Measurement layer, and Interface. MAC layer controls and communicates with hardware to get RF signals from anchors. Measurement layer translates received RF signals into either location or distance information. Interface is either RF or UART to report the measurements in a messaging protocol to the upper layer. Module Driver part comprises 4 sub-layers: Interface, Input Queue, Parser, and Reorganizer. Interface is hardware components to receive defined messages from localization modules. Input Queue is a queue which stores data from the lower layer and prepares them for processing. Parser extracts attributes in a message format received and Reorganizer stores them in a canonical format with additional information to process. Power Management Unit provides efficient power consumption by utilizing sleep/wakeup mechanism for unavailable modules. Integration part consists of 4 sub-layers: Pre-filtering, Fusion, Localization, Post-filtering. Pre-filtering layer mainly deals with checking and identification of validity of both anchors and measurements data with the defined modeling. Fusion layer integrates all measurements from different modules, and selects among them in a way to increase accuracy and reliability. Localization layer processes mathematical calculations to obtain location according to selected measurements from Fusion layer. Post-filtering layer is optional. This layer deals with probabilistic estimation to compensate uncertainties.

Application Interface is wired or wireless channels to report localization results to mobile robots or external devices. Anchor Management Unit manages anchor information from internal memory or external servers, and provides translation of coordinate systems.

Key function of the proposed framework is to provide the way of integrating indoor and outdoor localization systems as addressing seamlessness and transparency problems.

- Seamlessness problem is stated as the framework should provide localization information continuously without gap, regardless of indoor, outdoor, or transition.
- Transparency problem is stated as the framework should provide the same form of localization services whatever underlying technologies are used.

It guarantees seamlessness by applying new localization method called adaptive integrated localization and transparency by designing new architecture of fusion. Adaptive integrated localization provides location fix even in exceptional cases like handoff during transition between indoor and outdoor, and the fusion architecture allows utilization of measurement data from anchors using different localization technologies for one location fix, differently from existing localization systems only can localize with more than three measurement data which are the same localization technology. In the following subsections, we describe new architecture of fusion and adaptive integrated localization in detail.

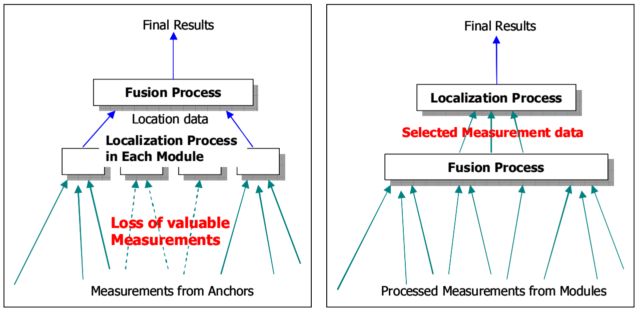
A. Fusion Architecture

In order to integrate multiple localization systems, existing fusion methods utilize location information, localization results from each module. During localization process in each module, more than 3 localization transactions are required at once for one location fix. In other words, only 2 or 1 measurement data are ignored or discarded as depicted in Figure 4-(a). This fact causes not only loss of valuable information but also unavailability of global localization during handoff between heterogeneous zones due to switching between localization systems, as shown in Figure 5-(b). Therefore, additional estimation process is required to compensate the gap in this case. However, it may fail when sharp turn or sudden change of speed is conducted.

As depicted in Figure 4-(b), our fusion architecture performs fusion as canonical forms of measurement data from each module before processing localization. This architecture can utilize measurement data from different localization technologies for one location fix as avoiding loss of valuable measurements. During handoff between heterogeneous zones, it can keep providing global localization services by activating an intermediate section which consists of combination of heterogeneous anchors, shown in Figure 5-(b). Since this process is not motion estimation but continuous services, it can adopt sharp turn or sudden change of speed.

B. Adaptive Integrated Localization

In order to enable the proposed framework to achieve seamlessness, we develop Adaptive Integrated Localization, the variation of least-square localization method based on decision tree. The method selects a localization algorithm according to the number of anchors available, N_A. As illustrated in Figure 6-(a), in case of N_A is larger than or equal to 3, location is solved by lateration using standard least-square approach.[8] On the other hand, when N_A is only 2, the two anchors are called as edge anchors, and we utilize them to calculate position using one-side construction method, as illustrated in Figure 6-(b). The unknown (x, y) is expressed as the following equation.



(a) Existing Fusion Method (b) Our Fusion Method

Figure 4. Fusion Architecture

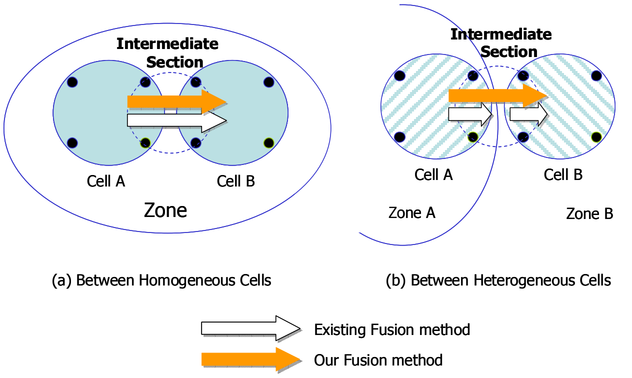


Figure 5. Handoff between Cells

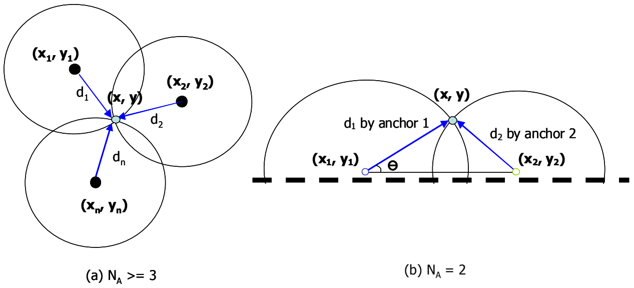


Figure 6. Lateration and One-side Construction

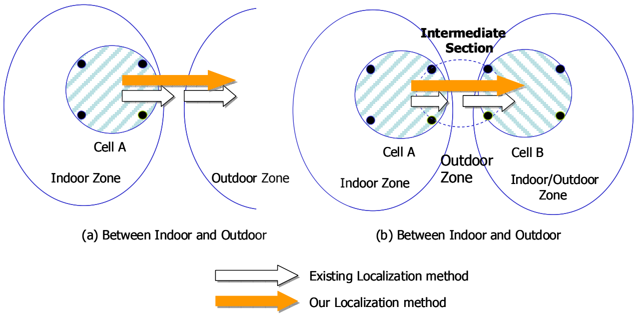


Figure 7. Handoff between Indoor and Outdoor

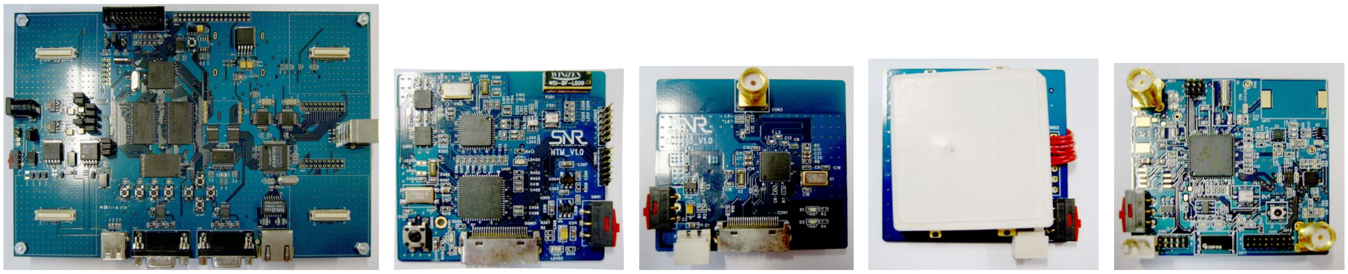


Figure 8. ANTS-IPS, ANTS-NTM, ANTS-CC2431M, ANTS-GPSM, ANTS-G2M (from left to right)

$$x = x_1 + d_1 \cos(\phi + \cos^{-1} \frac{d_1^2 - d_2^2 + D^2}{2 d_1 D})$$

$$y = y_1 + d_1 \sin(\phi + \cos^{-1} \frac{d_1^2 - d_2^2 + D^2}{2 d_1 D})$$

where, $D = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$ and $\phi = \tan^{-1} \frac{y_2 - y_1}{x_2 - x_1}$

Existing localization method which only use least-square method, works only when more than 3 anchors are available and inside of cells. The localization accuracy is dramatically decreased outside of cells and eventually not available. This causes gap of localization service during handoff between translation indoor and outdoor to reach outdoor zone like GPS, as illustrated in Figure 7. By applying proposed localization method, two edge anchors can provide localization services safely until GPS zone is reachable. In addition, whatever combination of anchors forms the intermediate section during transition, the region is able to improve the accuracy of localization with GPS as well as compensate the gaps of availability of GPS.

IV. INTEGRATED LOCALIZATION SYSTEM

Integrated Localization System is a platform to provide seamless and transparent global location information for mobile robots anytime and anywhere by embodying the proposed framework. The localization system utilizes a hybrid method which combines indoor localization systems based on WPAN and WLAN RF technologies with an outdoor localization system based on GPS. It consists of localization modules to interface with one of various localization technologies and a localization main board to integrate the measurement information from the modules and provide final location fix. This system is based on ANTS [9], new platform for wireless sensor network by RESL of Information and Communications University (ICU).

A. Localization Main Board

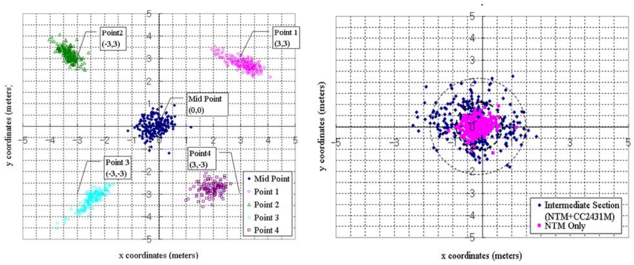
ANTS-IPS is the localization main board which utilizes Samsung 32-bit S3C2410 microprocessor based on ARM920T core. As external communication interfaces, 2 USB, 2 RS232, RJ-45, CDMA module are adopted, and 4 additional UART expansion connectors for localization modules are equipped in four corners of the board. Each localization module is connected into the connectors, and maximum 4 modules are available simultaneously. The power is provided via DC adopters, batteries, or USB input. Only essential parts of the proposed framework are implemented. When the application of the localization main board is started, the main function creates 5 POSIX threads. 4 threads concurrently check 4 UART channels for module outputs all the time, receive data when they are arrived, and store them into respective input queues. The data coming within one epoch are parsed, filtered, evaluated, and reorganized sequentially. The reorganized data are delivered to an integration thread which deals with the localization engine. Finally, the location is calculated by adaptive integrated localization. Post-filtering layer is not considered in this implementation.

B. Localization Modules

The localization module takes charge of direct interface on specific localization technologies. ANTS-NTM is a localization module in charge of IEEE 802.15.4a protocol. This module is realized by Nanotron NA5TR1 transceiver which provides distance estimation through two-way time-of-arrival (TW-TOA) method based on chirp spread spectrum (CSS), one of IEEE 802.15.4a standards. 8-bit ATmega128L microprocessor is used for a main processor. In current implementation, we assume that there is only one tag and 4 anchors. After initializing hardware, it searches iteratively anchors one by one. First, ranging request is transmitted to the address of the first anchors. If the reply of ranging is arrived and two-way measurement is complete, the result of distance measurement is returned. If there is no reply, the ranging request is repeated 10 times. In either measurement success or maximum number of requests, the destination of ranging requests is updated to the next anchor: anchor 2, anchor 3, anchor4, and anchor 1 again. The measurements by TW-TOA are reported via UART. ANTS-CC2431M is a localization module in charge of IEEE 802.15.4 protocol. This module is realized by Chipcon CC2431 chip which measures distance by estimating attenuation of received signals. Despite CC2431 chip can provide location measurement directly with hardware location engine, we disable the function, and make it offer the distance measurements in order to activate an intermediate section. ANTS-GPSM is a localization module in charge of GPS for outdoor localization. Dusitech GX-335A GPS module and ATmega128L microprocessor are used. Lastly, ANTS-G2M is a localization module in charge of Wi-Fi and RFID protocols. This module is realized G2microsystems G2C501 chip, but development of this module is not complete yet.

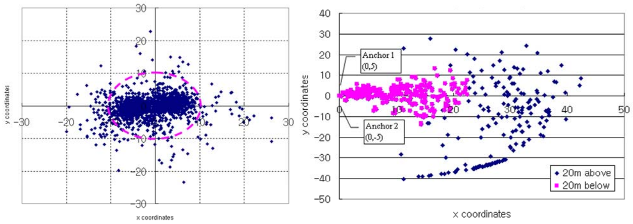
V. EXPERIMENTAL RESULTS

In this section, we evaluate the performance of the proposed framework with real experiments. ANTS-NTM modules were used to measure localization accuracy and availability in indoor environment. In addition, in order to validate an intermediate section, we tested localization accuracy in the infrastructure which consists of 2 ANTS-NTM anchors and 2 ANTS-



(a) NTM (b) Intermediate Section

Figure 9. Localization Accuracy



(a) Original Cell (b) Extension

Figure 10. Cell Availability

CC2431M anchors. Finally, based on the experimental data, seamlessness of Integrated Localization System is evaluated.

For indoor localization, the experiment was conducted in the wide student's hall inside of a lecture building in ICU. 4 anchors are installed in corners of 10m x 10m grid. In Figure 9, anchor 1 is located on (5,5), anchor 2 is on (-5,5), anchors 3 is on (-5,-5), and anchor 4 is on (5,-5). In order to evaluate the localization accuracy of NTM, we measured 200 samples and calculated the position in five fixed points. The first fixed point is located on the origin, (0,0). The other 4 fixed points are located on (3,3),(-3,3),(-3,-3), and (3,-3). As illustrated in Figure 9-(a), 80% of localization results are in boundary of circle with radius 0.5m. The results are highly accurate except bias errors are induced in point 4.

To verify capability of an intermediate section we define, we replaced two NTM anchors with two CC2431M anchors. 2 NTM anchors are located on (5,5) and (-5,5), and 2 CC2431M anchors are located on (-5,-5) and (5,-5). Figure 9-(b) depicts localization accuracy of the IS on point of (0,0) compared to that of NTM. Even though the results are spread out further, they are bounded into circle with radius 2m, mostly within 1.5m. This result shows possibility to provide improvement of seamlessness and mitigation of degradation of localization accuracy when only localization system like GPS which has low accuracy is available.

Finally, in order to evaluate seamlessness of this system, we validated the proposed localization algorithm and handoff method. We set two NTM anchors on (0,5) and (0,-5). The start point to measure is the origin. Figure 10-(b) shows high localization accuracy, especially within the point of 10m along x axis. Maximum error in the interval of first 20m bounds in ±10m. However, the interval of 20m above shows very high uncertainties due to available localization range of NTM. With several tests, the distinct data sets commonly presents very high usability of two edge anchors within the range of 10m, and possibility of localization within the range of 20m while no other system is available. As a result, by utilizing two edge anchors when no valid cell is available, especially for handoff during translation of indoor and outdoor, the availability of cell can be extended at least 1.5 times, possibly 2.5 times to that of the original cell, in Figure 10-(a) which does not activate the new localization method. The extended availability can guarantee the requirement of conversion time to GPS, approximately 10 seconds by experiments.

VI. CONCLUSION

The proposed framework provides abstraction of seamless and transparent global localization services for mobile robots in both indoor and outdoor. The mobile robot can utilize the localization services without knowing the detailed technologies during its operation. This provides ease of use and development. Experimental results show high indoor localization accuracy, reasonable localization accuracy of Intermediate Section, and extension of cell availability by adaptive integrated localization. As a result, we show that the proposed framework achieves reasonable localization accuracy as addressing seamlessness, especially during transition between indoor and outdoor, and transparency of underlying localization technologies.

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