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Abstract of Thesis

Name （ 周 恒 Heng Zhou）	
Title	Research on Enhancing Object Localization in GPS-Challenged Environments (GPSが制限された環境での物体位置推定の精度向上に関する研究)

Abstract of Thesis

The Global Positioning System (GPS) has revolutionized location tracking and navigation, enabling applications ranging from commercial logistics to personal navigation and wildlife monitoring. However, GPS technology is significantly hampered in environments where satellite signals are obstructed by physical barriers such as buildings, dense foliage, or subterranean layers.Such environments necessitate alternative solutions to ensure reliable and precise location data, especially in indoor and underground settings where traditional GPS is ineffective.

The primary challenge in these GPS-challenged environments is to mitigate the loss of reliable satellite signals, which is crucial for the accuracy of GPS systems.In response to this, localization methods such as dead reckoning (DR) have been adapted. Dead reckoning estimates an entity's current location based on its previously known position, employing internal sensors like accelerometers and gyroscopes to track movement.However, this method is inherently prone to accumulating drift errors due to inaccuracies in sensor data and the absence of external reference points to recalibrate the path calculated by DR.

To overcome the limitations of dead reckoning, several sophisticated approaches integrating with environmental landmarks have been developed. These landmarks, which are annotated with distinct physical or signal-based features in the environment, provide external references that help calibrate and correct the estimated trajectory. However, this integration of landmarks with dead reckoning poses specific challenges that vary significantly across different environments. Firstly, in infrastructured settings-environments that have been artificially constructed with features like floors, walls, and Wi-Fi signals -such as buildings, subways, and underground malls, the selection of appropriate landmarks involves identifying low-cost solutions that are ubiquitously available and do not require extensive site surveys.

Currently, there are some kinds of landmarks used in indoor environments that might include Wi-Fi or Bluetooth signal heat-map, and even architectural features like staircases but they are limited due to their high cost and low density, respectively. The challenge here lies in choosing landmarks that are both detectable and reliable over time without necessitating substantial upfront investment or ongoing maintenance. The second challenge is to effectively utilize these landmarks with dead reckoning systems to correct drift errors, which requires the development of sophisticated algorithms. This algorithm must not only output the user's trajectory based on sensor data from accelerometers and gyroscopes but also correct this trajectory using environmental landmarks based on location and time, with the assistance of another smartphone-embedded sensor. Furthermore, the requirement of prior known starting positions is also a restriction to dead reckoning's applicability. To achieve our research goal of object localization in GPS-challenged environments, we must also consider scenarios where artificial infrastructure is absent. Therefore, the third challenge is to adapt dead reckoning for underground environments, such as animal-dug tunnels, where traditional landmarks are typically non-existent. This is particularly crucial for tracking small animals, where the absence of human-made infrastructure necessitates innovative approaches. Here, the approach shifts towards adapting dead reckoning to operate in three dimensions, accounting for the intricate and dynamic nature of subterranean tunnels. This adaptation is technically demanding and requires innovative thinking to identify new types of landmarks that can function in such environments. Current mainstream methods for animal tracking often rely on computer vision technologies, but installing such systems, such as cameras, in underground conditions presents practical and technical difficulties.

To address the first challenge of finding easily accessible, cost-effective landmarks and generalizability, which refers to the ability of a system to fuse with different systems under various conditions, in indoor environments, we have innovated a new kind of landmarks -- "GPS landmarks." We developed a method that integrates indoor floor plans, outdoor buildings maps, and satellite positions to generate a detailed GPS map of signal reception like WiFi signal strength heat-maps. We used collected information of GPS satellites signal strength as output to train a neural network to learn signal propagation patterns, focusing on both regression and binary classification tasks. We collected data from 10 different environments in both sub-urban and urban areas and evaluated our method. In

practice, this method has achieved a 74% accuracy of predicting high signal strength position.

To address the second challenge of utilizing new landmarks to correct dead reckoning in indoor environments, we proposed a new method with existing GPS landmarks. Specifically, we identified areas near windows where GPS signals, although not consistently reliable throughout the entire space, can provide useful satellite signal information, including satellite identifiers, positions, and signal strengths at various times. By analyzing this information, we can infer the spatial relationship between the user and the GPS landmarks. This information is then fused with continuous dead reckoning data through a particle filter, which efficiently combines these sporadic GPS readings with the sensor-driven estimates of movement. This solution does not rely on a predefined starting position, enhancing flexibility for users. Our evaluation in diverse indoor settings shows that this GPS landmark-based dead reckoning system effectively minimizes drift errors, achieving a mean absolute error of approximately 1.2 meters relative to the ground truth.

Finally, to solve the third challenge of accurately tracking movements of small animals in underground environments, where traditional GPS and indoor positioning systems falter, we proposed an innovative method tailored to complex, three-dimensional spaces with additional magnetic field information. Our approach utilizes a magnetometer to capture the characteristics of magnetic fields generated by nearby rotating magnets. The captured features of magnetic fields by a magnetometer are then integrated with 3D change of direction and length predictors to accurately calculate the trajectory of a mouse by particle filter. To validate the efficacy of our proposed method, we collected 1 hour and 30 minutes of active movement data from mice. From this dataset, we performed cross-validation for detailed evaluation. Our method could achieve a mean absolute error of only 3.4 centimeters.

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論文審査の結果の要旨及び担当者

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論文審査の結果の要旨

提出された論文では、GPSによる測位が困難な環境における物体の位置推定を目的とし、GPS衛星からの特徴的な信号をランドマークとして用いる手法および、野生の地下環境に導入した磁石からの磁場をランドマークとして用いる手法の提案について述べている。

GPSによる測位が困難な環境では、慣性航法（Dead Reckoning: DR）などの位置測位方法が利用されている。慣性航法は、加速度センサやジャイロスコープなどのセンサを利用して、既知の開始位置から移動軌跡を推定する手法である。しかし、この手法にはセンサデータのドリフト誤差により位置推定誤差が蓄積していく問題がある。本論文では、そのようなドリフト誤差を低減するための新たなランドマークの提案およびそれを慣性航法に組み入れる技術に関して、以下の通り述べている。

１つ目の主な成果として、GPSランドマークを活用した慣性航法手法を提案した。具体的には、屋内の窓の近辺のGPS信号が得られるエリアをGPSランドマークとし、衛星の位置や信号強度といったユーザ端末の計測情報を基に、ユーザが訪れているGPSランドマークを推定することで、慣性航法の累積誤差を解消する。さまざまな屋内環境での評価において、このGPSランドマークを用いた手法は既存の慣性航法手法の誤差を大きく下回った。２つ目の主な成果として、屋内のフロアプランマップ、屋外の建造物マップ、衛星の位置情報を基に、Wi-Fi信号強度のヒートマップのようなGPS受信信号マップを屋内環境を対象に生成する手法を開発した。GPS衛星信号の強度に関する情報を様々な屋内環境で収集し、それを基にGPS衛生信号の伝播パターンを学習した。この手法を都市部と郊外の10の異なる環境で評価し、高い予測性能を達成した。３つ目の主な成果として、野生の地下環境における小動物の動きを追跡するために、磁場情報を利用した慣性航法を提案した。この手法では、回転する磁石によって生成される磁場の特徴を磁力センサにより捉え、その情報を用いて慣性航法の累積誤差を解消する。

本論文は、GPSによる測位が困難な環境における物体の位置推定を実現するための基礎技術を実現した。特に、屋内で観測されるGPS衛星からの信号を屋内位置推定に利用する手法はこれまでに提案されておらず、新規性が高い。また、磁気センサを用いた慣性航法手法を小型動物の追跡に適用し、異分野融合研究に貢献した。本論文により達成された成果は、GPSによる測位が困難な環境における様々な物体の位置情報へのアクセス性を高める先端的な情報技術手法の研究として、情報科学に寄与するところが大きい。よって、本論文は博士（情報科学）の学位論文として価値のあるものと認める。