엣지-클라우드 시각적 SLAM: 대역폭 절약을 위한 IBF 기반 이미지 특징점 전송 및 복구

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Edge-Cloud Visual SLAM: IBF-based Image Feature Transmission and Recovery for Bandwidth Saving

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Abstract

Simultaneous localization and mapping (SLAM) is a key technology that enables a robot to build a map of its surroundings in real time and estimate its own position at the same time. This function is essential for autonomous mobile robots, but visual SLAM (vSLAM) utilizing camera-based sensors often requires significant memory and computational resources, making it difficult to perform continuous tasks on resource-constrained mobile platforms. To address these limitations, edge-cloud collaborative vSLAM systems have been introduced to offload computationally intensive tasks to cloud servers. However, transmitting all frame-by-frame feature points to the server incurs significant network overhead. In this paper, we propose an image feature point transmission method based on the Invertible Bloom filter (IBF). The IBF, a compact and efficient data structure suitable for on-chip implementation, enables fast and lightweight feature point processing, making it well suited for real-time vSLAM applications. Through performance evaluation, we demonstrate that the communication volume can be significantly reduced by effectively removing redundant feature points between consecutive frames, and that the original feature points can be fully recovered at the edge server without loss through d-IBF decoding, which can be efficiently implemented with a hardware accelerator.

Ⅰ. Introduction

Simultaneous localization and mapping (SLAM) is a key technology in autonomous vehicles and indoor robots, which maps the environment and estimates the current location using LiDAR and camera sensors. Among them, visual SLAM (vSLAM) uses image sequences as input and is widely used in Industry 4.0 environments, especially with the development of Mobile Industrial Robots (MIR). However, vSLAM requires high computational resources and is difficult to run independently on power-constrained mobile devices. Lightweight feature extractors such as Oriented FAST and Rotated BRIEF (ORB) can operate on embedded devices, but these devices still have limitations in transmission and autonomy. Minimizing communication overhead remains an important challenge in limited network environments, as transmitting many feature points causes communication delay and bandwidth consumption. This paper presents a novel IBF-based feature point transmission method within an edge-cloud visual SLAM (vSLAM) architecture to effectively reduce communication overhead. Unlike the conventional method that transmits the entire frame features, the proposed method can remove common features between adjacent frames while transmitting the features of the entire frame as IBF, resulting in a communication amount proportional to the number of distinct features. Furthermore, this paper provides a theoretical analysis comparing the raw feature transfer scheme with the proposed IBF-based scheme and demonstrates the ability to recover the full feature set at the server without any information loss through a d-IBF decoding hardware accelerator implemented using Verilog HDL.

Ⅱ. Related works

Cloud-based SLAM architecture has been proposed to distribute the computational load of multiple robots to the cloud and is utilized for real-time processing of high-resolution images or video streams. However, as multiple sensors transmit data simultaneously, the communication volume and delay increase rapidly. Accordingly, edge computing-based vSLAM has emerged, which performs only lightweight preprocessing locally and delegates computationally intensive processing to edge servers. Recently, a method to reduce data through implicit representation [1] transmission has been proposed, but this is not suitable for real-time systems due to complex computation. In addition, the FREF (Feature Representation of Every Frame) method [2], which transmits features of all frames, can improve map quality, but increases the communication volume compared to the keyframe-based method. In this method, the ORB algorithm is used to extract image features, and the ORB consists of a FAST-based keypoint detector and a BRIEF-based binary descriptor. IBF is a probabilistic data structure derived from the existing Bloom Filter, and it can be inserted, deleted and recoverd, and supports a concept called difference-IBF (d-IBF), which can recover the difference between two sets. Each cell consists of three fields: *idSum*, *sigSum*, and *count*, and they are accumulated and stored in hashed locations for each feature point in the XOR manner. When the difference between two IBFs is calculated, duplicate elements are removed, and only distinct elements remain. Based on this, cells satisfying the pure cell condition (*count* = 1, g(*idSum*) = *sigSum* can be repeatedly decoded to recover the entire distinct feature [3].

Ⅲ. Our Approach

In our approach, we propose an image feature transmission method based on Invertible Bloom filter (IBF) to reduce the amount of data transmission in edge-cloud visual SLAM systems. In the proposed method, feature points of the entire frame are programmed into the IBF and transmitted, but common feature points are removed through the d-IBF, so the communication amount is proportional to the number of distinct feature points that exist only in each frame. In addition, the server can accurately recover the original feature points in real time without information loss through d-IBF decoding using a hardware accelerator. Figure 1 shows the reduction of one-round communication volume from the first key frame (K0) of VisDrone (V_Set) data to the next key frame (K1), which is reduced by 77.07%.

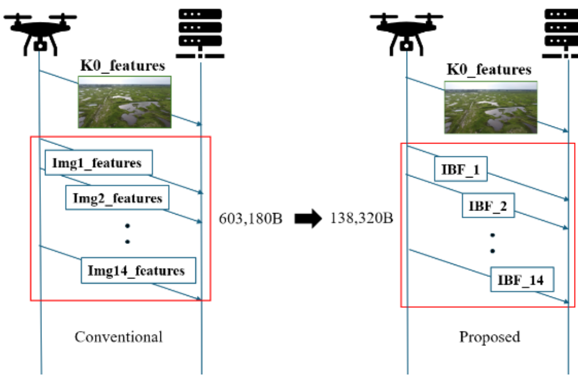

Figure 1. Comparison of communication volume

Figure 2 visualizes the entire system architecture. accelerator. The mobile robot, which is a sensor node, extracts ORB features from the captured image, programs them into the IBF, and transmits them to the server. The server that receives the feature point data can recover the original features without information loss, and the programming and decoding can be performed by a hardware accelerator.

Ⅳ. Evaluation & Conclusion

We performed experiments on the success of d-IBF decoding and communication volume comparison after extracting image feature points through the ORB algorithm using three public datasets, VisDrone (V_Set), KITTI (K_Set), and TUM (T_Set).

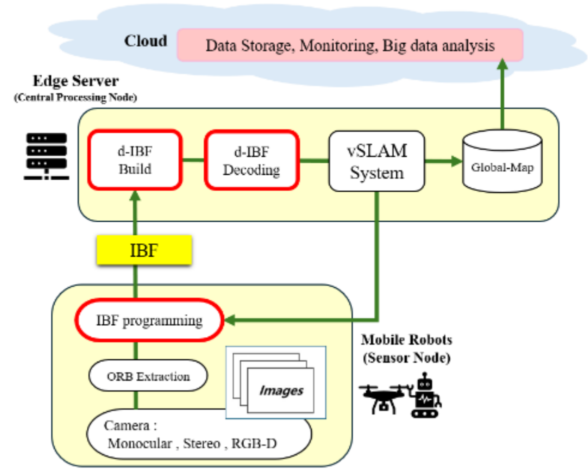

Figure 2. Proposed Entire Architecture

As a result, the proposed method successfully recovers the features of all datasets through the d-IBF decoding hardware accelerator designed in Verilog HDL and shows a total communication volume reduction rate of up to 73.97% compared to the conventional methods. VisDrone (V_Set) showed the highest reduction rate of 73.97% due to many common features between consecutive frames. The remaining datasets, KITTI (K_Set) and TUM (T_Set), showed reductions of 43.59% and 24.8%, respectively. These results suggest that the proposed method reduces the communication amount with more common features in an environment with little movement and provides high transmission efficiency on average even in various situations. Therefore, the IBF-based transmission structure proposed in this paper is a lightweight solution that can significantly improve the communication efficiency of SLAM systems and can operate efficiently on real edge devices through hardware acceleration.

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Reference

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