COOPERATION OF CPU AND GPU PROGRAMS FOR REAL-TIME 3D MAP BUILDING

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Abstract: This paper presents how the CPU and GPU programs coordinate in the context of 3D map modeling for a mobile home service robot. In this study, the representation of the environment is given as point clouds, and each scan of point clouds is quite efficiently processed using the parallel processing capability of GPU. Then, the result is read back to CPU for incrementally constructing the map. Due to the coordination between the CPU and GPU, a 3D map can be built at real time. This paper presents the software architecture of the CPU-GPU coordination, the GPU algorithm, and its performance gain.

1 INTRODUCTION

Recently, much attention has been directed to home service robots such as cleaning robots while the markets for conventional industrial robots are saturating. A home service robot requires a *map*, which is a spatial model of the physical environment. In our study, the environment is first captured as *point clouds*, and then a 3D map is incrementally constructed from the successive inputs of the point clouds. Noting that a lot of planar surfaces, such as walls and floors, exist in a typical indoor environments, we propose to extract the plane information and store it into the 3D map.

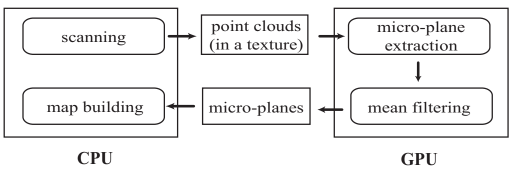

Figure 1: CPU-GPU coordination.

The algorithm proposed in this paper utilizes both the CPU and GPU (Graphics Processing Unit) for building a map with planar features included. The coordination between them is illustrated in Fig. 1. First of all, the scene is scanned and the point clouds are stored in a *texture*, which refers to a rectangular array of *texels*. Then, the texture is passed to GPU. Two tasks are done by the GPU: (1) a *micro-plane* is extracted for each point, and (2) the micro-planes are smoothed using mean filtering. Finally, the buffer storing the micro-planes is read back to CPU, and the CPU builds a 3D map which contains plane information of the environment.

This paper presents the micro-plane extraction and mean filtering algorithms, and shows why they can be efficiently implemented in GPU. (Presenting the map building algorithm is beyond the scope of this paper.) The performance of the GPU implementation is presented, and is also compared with the CPU implementation of the same algorithm.

2 MOBILE ROBOT AND WORKING ENVIRONMENT

Fig. 2-(a) shows the experimental robot and a section of the home environment used in the experiment. The time-of-flight camera mounted on the robot scans the environment at 5 frames per second (fps). Consequently, the complete process of scanning a scene, registering it into the previous scans, and constructing the 3D map is done in 200 msec. A scan's resolution is 176×144. The section of the home environment shown in Fig. 2-(a) requires 5 scans, and Fig. 2-(b) shows the result of rendering the 3D points in a scan. (Each point of the scan is represented as a 3D point, and therefore can be directly rendered.) Fig. 2-(c) visualizes the final 3D map representation, where the planar features are colored in red. (The points that are

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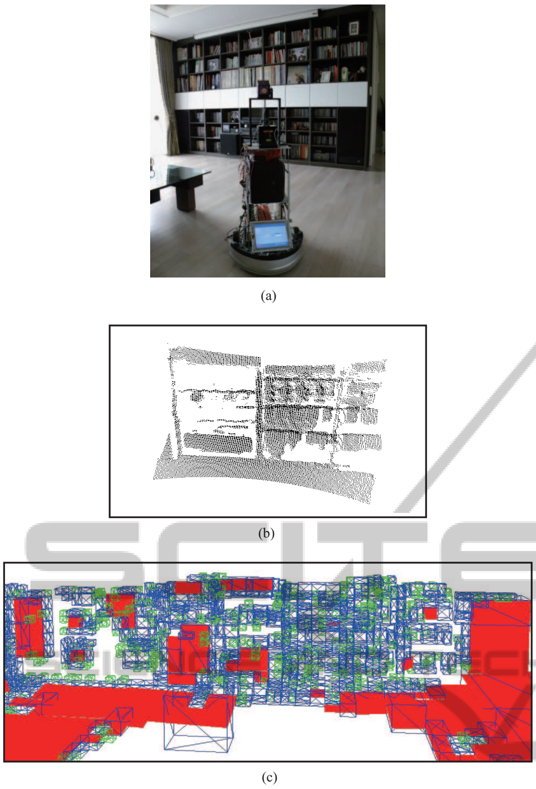


Figure 2: Indoor environment and its 3D map. (a) The robot and a section of the environment. (b) The point clouds of 'a' scan for the section. (c) The 3D map representation with the planar features included. (This is the output of the CPU program.)

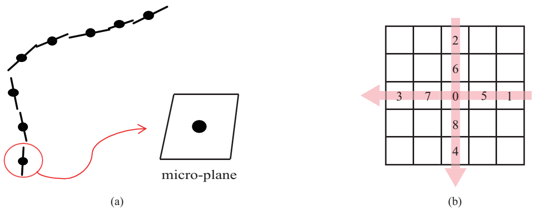


Figure 3: Micro-planes and normal computation. (a) A micro-plane is presented by a point's position and normal. (b) A micro-plane's normal is computed using the position information of the neighboring points.

not included in the planar features are illustrated as wireframe boxes containing the points.)

3 MICRO-PLANE EXTRACTION

In order to help the CPU detect the planar features of the indoor environment, the GPU extracts the *micro-planes* from the scanned points. For each point of a scan, a micro-plane is extracted. As shown in Fig. 3-(a), it is defined as an infinitesimal plane centered on the point. To define its orientation, we have to compute the normal. Fig. 3-(b) shows a block of 5×5 points in a scan. The normal of the center point (point 0) is computed as the cross product of the vector connecting points 1 and 3 and the one connecting points 2 and 4.

The GPU has a massively parallel processing architecture such that hundreds of cores independently operate on texels. A core is assigned to a texel to extract a micro-plane. The parallel architecture of the GPU allows very efficient manipulation of large bulks of data, i.e., 176×144 texels in a scan.

Unfortunately, a lot of noises are generated in the extracted micro-planes, i.e., the points sampled from a real-world plane may have different normals. For the purpose of de-noising, the GPU program uses a mean filter (Boyle and Thomas, 1988). In the current implementation, the filtering process is iterated five times. The parallel architecture of the GPU also fits to the filtering algorithm.

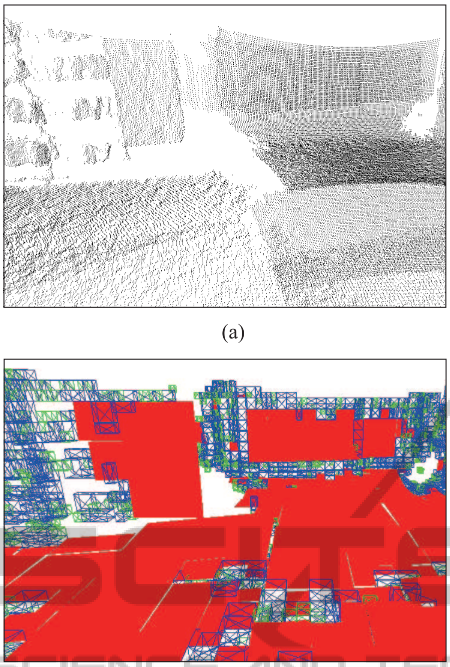
The map building algorithm implemented by CPU constructs a larger plane using a set of micro-planes. The red-colored features shown in Fig. 2-(c) are the planes extracted by the CPU algorithm. (Presenting the map building algorithm is beyond the scope of this paper.)

4 IMPLEMENTATION AND EXPERIMENTAL RESULTS

GPU plays a key role in our study. This kind of approach of solving non-graphics problems on GPU is known as general purpose computation on GPU (GPGPU). The micro-plane extraction and mean filtering algorithms are implemented in CUDA (Compute Unified Device Architecture) (Nickolls et al., 2008).

The algorithms for micro-plane extraction and mean filtering take about 5msec per 176×144-resolution scan. For comparison, we also implemented the same algorithms in CPU, and found they take approximately 150msec, i.e., they are about 30 times slower than the GPU algorithm. Recall that our goal is 5 fps map building, i.e., 200msec is assigned to a scan. The CPU implementation makes it hard to achieve the goal. It is because, in addition to micro-plane extraction (and mean filtering), the module for 'map building' shown in Fig. 1 should also be done within 200msec. Unfortunately, 'map building' typically takes more time than micro-plane extraction and mean filtering.

Fig. 4 shows the experimental result for another



(a)

(b)

Figure 4: Another test result. (a) Point clouds. (b) 3D map.

section of the home environment. Fig. 4-(a) is the rendering result of the input point clouds from multiple scans, and Fig. 4-(b) shows the 3D map where the planar features are colored in red. The entire process of scanning, micro-plane extraction, mean filtering, and map building takes about 70msec per scan.

5 CONCLUSIONS

A 3D map might be provided in advance to a mobile robot, but it is not always possible especially for a dynamic environment. Therefore we need to construct the map at real time. In our study, the home service robot scans the environment five times per second, and updates the map on the fly. Such real-time performance is achieved largely due to GPU implementation of the micro-plane extraction and mean filtering algorithms. The input point clouds are massive (176×144 resolution) and independent of each other. The parallel processing capability of many-core GPU proves to satisfy the real-time constraint.

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