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Omni-VISER: 3D Omni Vision-Laser Scanner

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Abstract

Three dimensional perception has drawn significant attention recently partly due to the success of Kinect and 3D lidar such as Velodyne. Although quite successful, they still have some limitations such as limited sensing range or high costs prohibiting them for small-scale outdoor applications. This paper presents a novel 3D scanning system by integrating a continuously rotating laser head with an omni-directional vision which offers a full 360° field of view with sweeping range measurements. An extrinsic calibration procedure is also proposed, in which point correspondences are being used instead of calibration object. Key benefits of the proposed system are 1) the capability to provide full 3D measurements after each revolution and 2) a real-time texture based 3D mapping. The paper presents the experimental results of prototype hardware for 3D point cloud generation with texture and feature detection. An open source implementation of real-time point cloud generation is also made available.

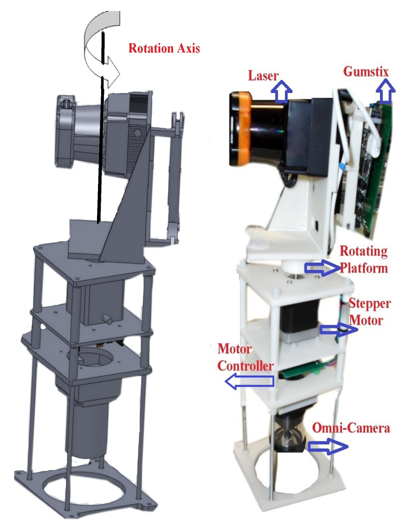


Figure 1: Omni-VISER (Omni-VISual lasER) a 3D scanning system by integrating a continuously rotating laser head with an omni-directional camera. (a) A CAD model. (b) A prototype hardware

1 INTRODUCTION

Three dimensional perception and mapping are one of fundamental tasks for autonomous robots which could be operating in outdoor and rough terrain environments. The acquired map can be used for navigation, path planning, collision avoidance and other high level tasks such as information gathering and monitoring.

With the recent success of the low-cost Microsoft Kinect, research on 3D sensing, called RBG-D sensing, has gained much attention recently from both computer vision and robotics communities [Henry et al., 2012]. Although quite promising, due to its limited detection range(3-4 meters) and small field of view, its use has been confined to indoor mapping applications.

In robotics, there have been significant efforts over the last few decades to use the 2D scanning laser to construct a 3D environmental map. One such method is to install a laser pointing vertically and scan sideways as a vehicle moves forward, resulting in a 2.5 dimensional map [Jochem et al., 2011]. To make the mapping process more close to real-time operation, a servo driver is usually attached so that the laser can scan a certain direction, such as forward. Such systems have been successfully used for 3D mapping such as abandoned mine [Thrun et al., 2004] and inertial integrated system[Katz et al., 2006]. Due to the difficulty in aligning each laser beam, the vehicle had to follow a stop-scan-go pattern which enables a whole frame alignment.

There have been recent developments on 3D sensors such as Riegel and Velodyne for the 3D reconstruction purpose [Nguyen C., 2010]. For example, Riegel sensor can be used for dense and accurate 3D point clouds which are typically processed off-line [Douillard et al., 2011]. Velodyne has a ca-

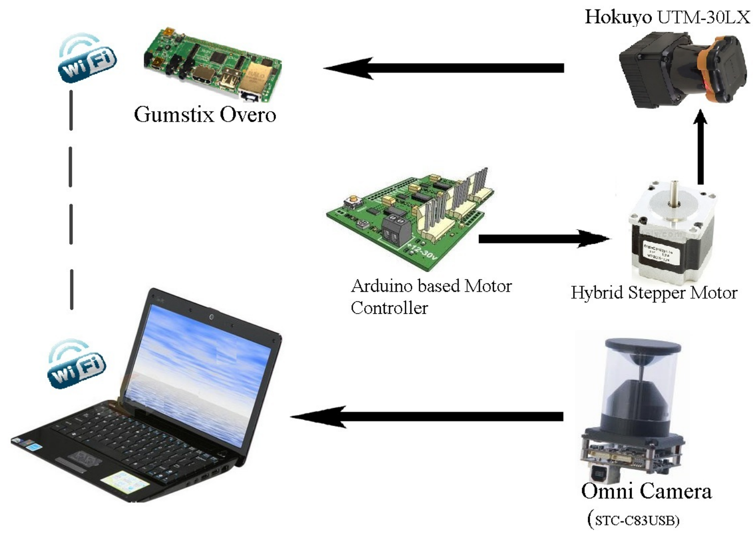


Figure 2: Systematic layout of the 3D scanning system

pability of scan on-the-fly and has showed potential for both navigation and urban street mapping [Douillard et al., 2012; Montemerlo et al., 2008]. Although 3D point clouds obtained from lasers are accurate to few millimeters in most cases, extracting and matching geometric features can be computationally expensive. Typically a scan matching algorithm should be performed and matching whole data points can be problematic for real-time applications. In addition, some sensors like Velodyne are high-cost ($> 0.5M$\$) prohibiting there uses for small-scale robotic platforms.

In the paper, we presents a novel 3D scanning system by integrating a continuously rotating laser sensor and omnidirectional vision system with the aim of real-time navigation and 3D mapping. The key benefits of the current configuration, which makes it better choice as against the recent 3D laser-only systems [Bosse et al., 2009; Hu S., 2009; Morales et al., 2011] are:

- Real-time 3D visual features (for 3D scan matching)
- Enhanced aiding capability of on-board navigation system due to its wide field-of-view
- Outdoor real-time 3D texture based reconstruction

A low-cost, real-time 3D acquisition system has a lot of potential to open up a vast range of new robotics applications. In this paper, we will present the development of the initial prototype system and scanning results in indoor conditions, also addressing various issues such as calibration.

The outline of this paper is as follows: Section 2 will provide a design details of the 3D scanner. Section 3 will briefly explain the 3D point cloud generation approach. Section 4 will provide a detailed discussions on the vision-laser calibration procedure. Results and discussions will be presented in Section 5 followed by Conclusion.

2 Design of Portable Visual Laser 3D Scanner

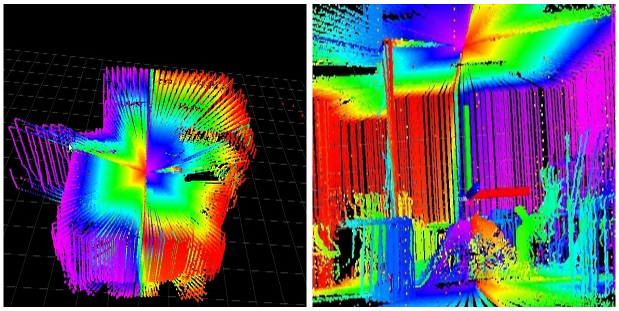
A custom rotary platform is designed for prototype system as shown in Figure 1, weighted 1.216kg. There exist various possibility to rotate the 2D laser scanner i.e. around the roll, pitch and yaw axis. Each setup has its own advantages but we choose yaw motion for 2D sensor to build 360° omnidirectional 3D point clouds. We considered a spinning platform design as against the two well known motor motion designs: slip rings (mechanically hard to make) and nodding laser scanner (which covers smaller field of view). Spinning platforms are less susceptible to timing errors as they can maintain a continuous rotational velocity.

For motion around yaw axis, we deploy a motor (Wantai stepper motor) on the base of the platform as shown in Figure 2. A motor controller is implemented on arduino based board to increase/decrease the speed of the motor. The motor spins the platform on which 2D commercial laser range finder [Hokuyo-UTM-30LX,] is attached with a dedicated processing board [Gumstix-Overo,] and power supply. The data is transmitted onto the IEEE802.11 link to a laptop which collects and process the data in real time. The laptop is directly connected to Catadioptric camera (STC-C83USB) attached to the base platform. The time synchronization is performed by using the master clock of the laptop for acquiring data from laser/vision system.

Hokuyo UTM-30LX provides a 2D scan with a field of view of 270° and with maximum scanning range of 30m and a minimum range of 0.1m ($\pm 50mm$). The prototype system is designed to utilize the best performance of both the sensors i.e. field of view.

3 3D Point Cloud Generation

The 2D scanner is placed upon the spinning platform which provides the fixed yaw/step at a regular interval of time to ob-



(a) (b)

Figure 3: 3D point cloud from the spinning laser, (a) Exterior view from top (b) Interior view

tain the 3^{rd} dimension of the laser data. The coordinates of 3D point cloud is obtained by range data (ρ) returned by laser with its beam elevation angle (θ) and the yaw/spin being provided (ψ). The 3D point cloud can be represented by (ρ,θ,ψ) in a cartesian coordinate by using the forward kinematics as follows:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \rho\cos(\theta)\cos(\psi) \\ \rho\cos(\theta)\sin(\psi) \\ \rho\sin(\theta) \end{bmatrix} \tag{1}$$

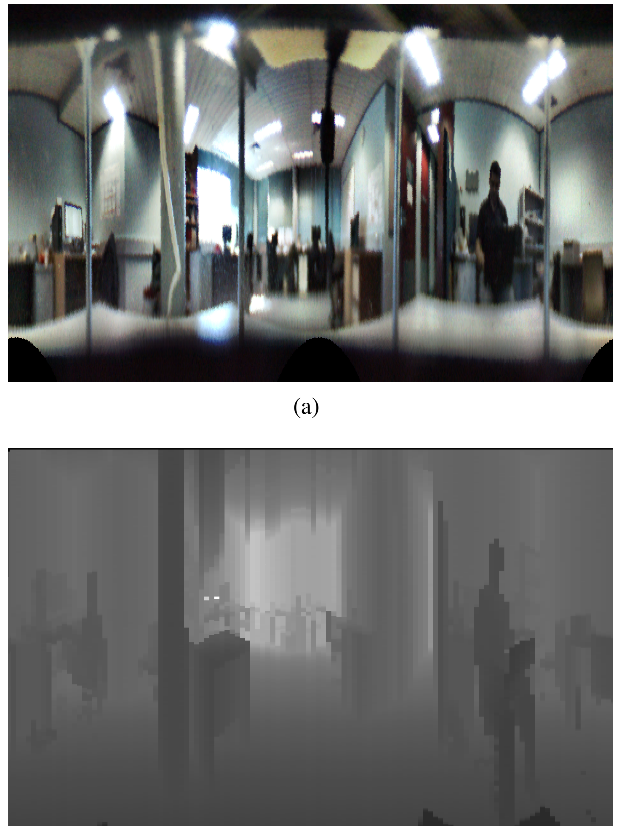
where M is a 3D point in the cartesian space with the coordinates x, y, z.

Figure 3 shows the point cloud generated from the spinning laser.

4 Extrinsic Calibration

Calibration is a process to estimate the common reference frame for multi-sensor platform. This work assumes that the internal calibration of the sensor is known and fixed whereas we have to estimate the rigid body transformation parameters $\{R,T\}$ between the camera and laser coordinate frame (known as extrinsic calibration). Generally the calibration object is utilized for extrinsic calibration [Qilong et al., 2004; Pandey et al., 2010], which is in-fact time consuming and quite laborious. We have used the depth image as against the color image of the omnidirectional camera as shown in Figure 4 and requires user intervention for selecting the corresponding points.

The premises is based upon the idea that laser and camera provide intrinsically different information but in terms of geometry there exist some common characteristics/features. This kind of commonality is mostly exploited in visual/laser registration [Peynot et al., 2010]. The close in spirit to our work is [Scaramuzza et al., 2007], whereas we have utilized the raw depth image instead of processed image. We have considered the presence of depth contrast between the color and depth image for feature correspondences (in our case, it is a reasonable assumption with larger field of view (360°) in cluttered environment).



(b)

Figure 4: After Calibration, (a) Unwrap color image and (b) Depth image from spinning laser.

The depth image is generated by combining all the range measurements of the 3D point cloud in a 2D matrix. An interactive GUI is presented to user to select common features between depth and color image. Once more than four features are selected, the least square solution [**?**] is calculated to obtain rigid body transformation as:

$$m = K[R\ T]M^{'} \tag{2}$$

Where m is the homogeneous image coordinates (u,v), K is the intrinsic parameters, $\{R,T\}$ represents rigid body transformation between laser and camera. $M^{'}$ is the 3D point M, defined in the homogeneous coordinate (corresponding to selected 2D depth image feature).

To estimate the optimal results, the rigid transformation estimated earlier (from different resolution sensors) is provided as a initial guess to a non-linear least square estimation:

$$min_{R,T}\ \sum_{i=1}^{n} ||m - K[R\ T]M'||^2 \tag{3}$$

5 Results

The proposed 3D scanning system and calibration approach has been tested on real data sets collected in a room environment. C++ within the Robotics Operating System (ROS)

Table 1: **3D laser scanner angular resolution analyzed against the motor speed with fixed acquisition rate**

Motor Speed (Hz)	**Horizontal Angular** (Resolution Deg)	**Laser Acquisition** Rate(Hz)
0.5	2.25°	40
1.0	4.5°	40
2.0	9.0°	40

[Quigley et al., 2009] was used on a Linux running Laptop/Gumstix, which provides the transparency in integrating different hardware modules with time synchronized data. The data was collected/processed in real time and the implementation for real-time point cloud generation is made available online[1]. The laser scanner is attached to Gumstix USB hub while effectively utilizing the bandwidth of USB interface by turning off the laser intensity data. The IEEE802.11 link between multiple Linux running machines (Gumstix, laptop) is time synchronized by network time protocol (i.e. ntp) to acquire the image and laser scanner data.

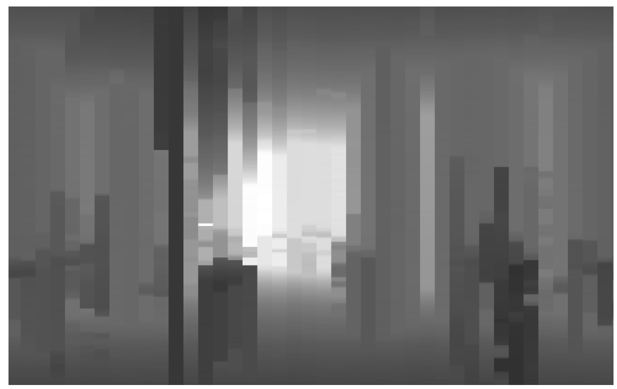
The camera resolution for the omni-directional camera was set to 1077*788 at 30Hz,with motor speed of 1Hz/2Hz for different data sets. The rotating scanner provides 360° field of view with vertical angular resolution of 0.25° at 40Hz. There exists a relationship between angular resolution, laser acquisition rate and motor speed as shown in Table 1. Increasing the speed of motor results in sparse point cloud with fixed laser acquisition rate, as depicted by their respective depth images in Figure 5.

Vision-Laser calibration proposed in this work was performed on a single 360° sweep of the laser scanner with an omnidirectional image. The calibration of the omnidirectional camera is assumed known. The re-projection error in our experiment comes up-to 1.9 pixels with standard deviation 1.3 pixels. As the ground truth is not available so visual accuracy is judged by utilizing the estimated calibration parameters. Figure 6 shows the overlay of laser scanner beams on omnidirectional camera to visualize the near/far range of the laser as against the corresponding camera frame. The starting, middle and ending portion of the roof pillar (labelled A,B,C respectively) can be compared with the laser projection to evaluate the visual accuracy (when motor is running at 2Hz). The accuracy evaluation of the calibration work with ground truth and modifying the cost function for non-uniform distribution of the spherical camera resolution [Mei et al., 2006] is left for future work.

The real time 360° point cloud with texture can be very helpful for different robotics applications i.e. surrounding environment awareness. 3D point cloud with texture is shown in Figure 7, which utilizes the transformation information from the calibration procedure performed earlier. As the resolution of the sensor is different, so linear interpolation is applied onto the depth image to assign each pixel with range values. The interpolation is a major source of noise which can be handled appropriately using visual information for interpolation [Andreasson et al., 2006], which is not the focus of this work.

[1]https://docs.google.com/open?id= 0B8gYxW2umHiVLUVPQmxrdVpWRzA

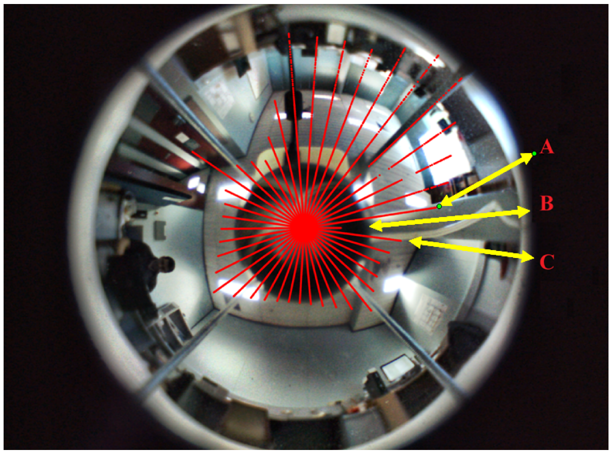
(a)



(b)

Figure 5: Sparseness of depth image as against the spinning speed of motor with acquisition rate at 40Hz. Depth image generated at spinning speed of (a) 1Hz and (b) 2Hz.

3D point clouds require 3D alignment algorithms, which are computationally very expensive for real time applications. Standard techniques solves data association problems at a point-to-point level. As we are generating the point cloud in real time so to perform alignment/matching, we fused laser data with visual corner features. FAST corner features [Rosten et al., 2006] are detected from the image and by utilizing the calibration parameters, their respective 3D range values are combined to get a 3D visual feature. Figure 8 shows the detected FAST features on the input image and feature-pruning is performed based upon uniform spatial sampling and availability of respective range data. The concept of 3D visual features can pave the way to real time ego-



(a)

Figure 6: Projection of laser beams onto the camera image after extrinsic calibration (laser beams are the maximum distance to the obstacle), to visually gaugue the accuracy of the system

motion/SLAM algorithms using the presented hardware in a dynamic scanning framework. The presented 3D visual features on our prototype hardware can provide effective tracking capability as compared to existing RGBD sensors, due to larger field of view and greater range detection capability.

As each visual pixel is assigned range data so to present the applicability of the demonstrated approach to obstacle detection (thresholding is applied on the range values greater than 3 meter) as shown in Figure 9.

Overall we have presented a prototype 3D omni-scanner with a vision-laser calibration approach, capable of detecting 3D color features and building a textured point clouds in real time, video is available online[2].

6 CONCLUSIONS AND FUTURE WORKS

6.1 Conclusions

A low-cost, real-time 3D acquisition system has a lot of potential to open up vast range of new robotics applications. In this paper, we have presented the development of the initial prototype system and scanning results in indoor conditions, also addressing various issues such as calibration and synchronization. The benefits of proposed configuration are: cost-effective, real-time 3D reconstruction with enhanced aiding capability of on-board navigation system due to its wide field-of-view. An open source implementation is also made available to robotics community.

6.2 Future Works

The future work will utilize the 3D visual features presented in this work for real-time SLAM on a moving vehicle. We will also look into the accuracy evaluation of the current system with the ground truth data.

[2]http://www.youtube.com/watch?v=k-W1tihen_M&feature=plcp

Figure 9: Application areas: Image segmentation based upon the associated depth data (Here, each pixel in Figure 4 (a) with range less than 3 meters is thresholded)

Acknowledgments

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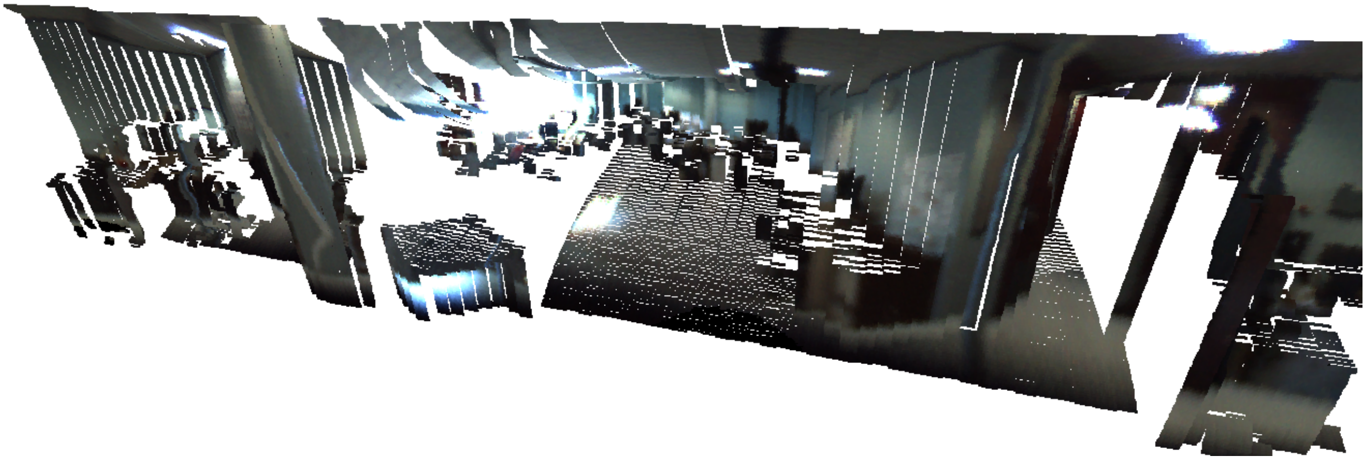

Figure 7: Application areas: 3D point cloud with texture mapped

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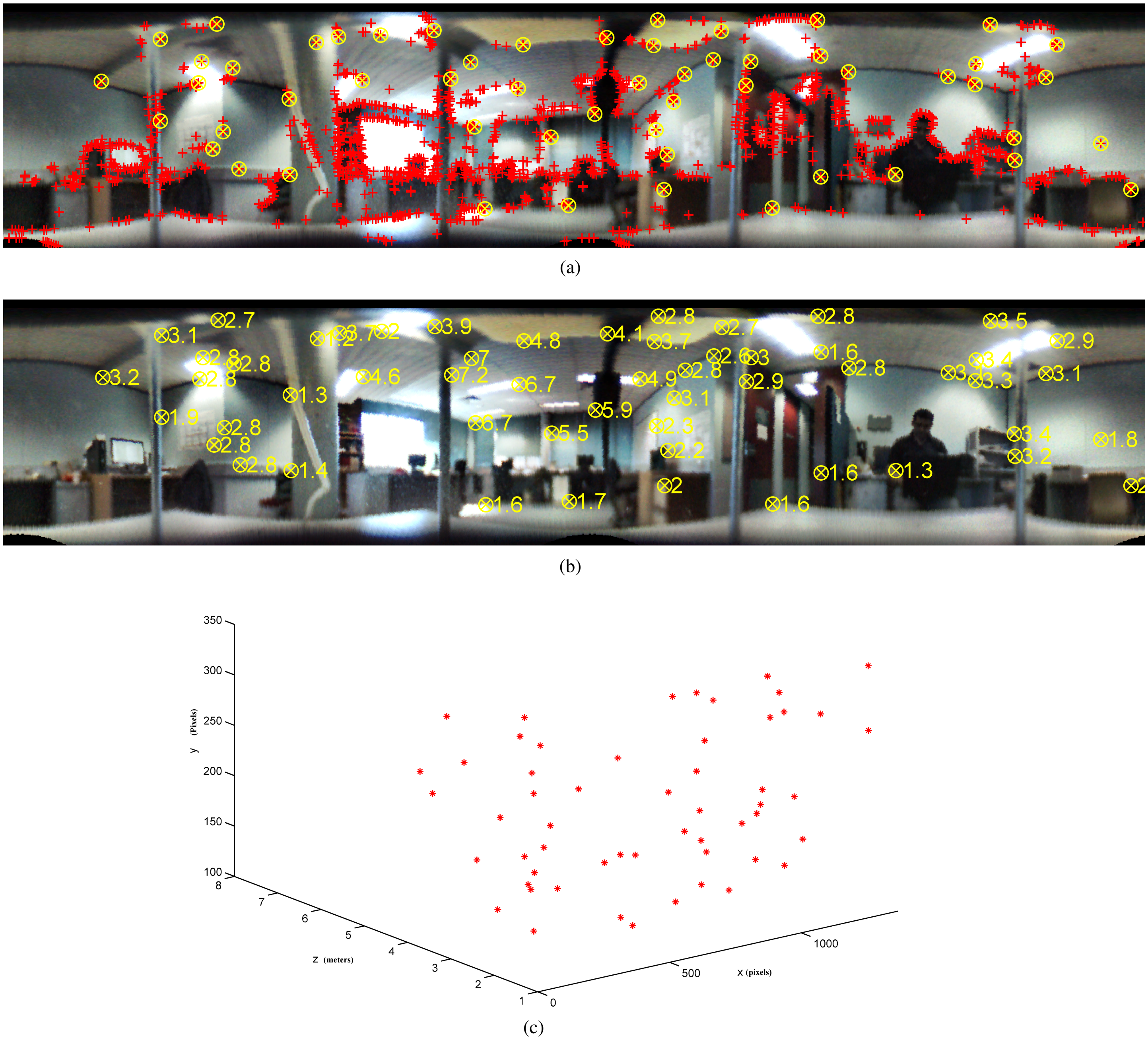

Figure 8: 3D visual features on our prototype Scanner. (a) Fast corner detected on the input image and (b) Spatial uniform sampling of the features with their respective range values. (c) Euclidean representation of detected features.