Thermal 3D Modeling of Indoor Environments for Saving Energy

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***Abstract*— Heat and air conditioning losses in buildings and factories lead to a large amount of wasted energy. The Action Plan for Energy Efficiency [4] of the European Commission estimates that the largest cost-effective energy savings potential lies in residential ($\approx$ 27%) and commercial ($\approx$ 30%) buildings. Imagine a technology that creates a precise digital 3D model of heat distribution and heat flow enabling one to detect all sources of wasted energy and to modify buildings to reach these savings. This video presents our approach to this task. Methods for creating a consistent laser scan model enhanced with information from thermal and optical cameras are presented.**

I. INTRODUCTION

Recently a lot of work has been done to capture and reconstruct the world around us. Thermal imaging is state of the art in recording energy related issues. However the acquired images tell the user precise temperatures without the dimensions of the heat or air lack. Reliable solutions to 3D reconstruction based on images have not been presented, yet. Terrestrial laser scanning has been used for years to create 3D models. Registration algorithms from the geodesy and robotics community combine laser scan data acquired at different positions into complete models of the environment. Think of a technology that enables one to gage the environmental structure in 3D and thermal information simultaneously. Precise thermal 3D models will enable architects and construction engineers to inspect the model, run simulations of heat and air flow and use the gained information to modify existing buildings to reach the estimated energy savings. This video presents our approach towards this goal. Further information including an extensive review of related work can be found on the project webpage [2].

II. SCIENTIFIC APPROACH

A. Experimental setup and data acquisition

The setup for simultaneous acquisition of 3D laser scan data, thermal, and optical images is the robot Irma3D. Irma3D is built of a Volksbot RT-3 chassis. Its main sensor is a Riegl VZ-400 laser scanner from terrestrial laser scanning. Two cameras are mounted on top of the scanner. The Logitech QuickCam Pro 9000 webcam has a video resolution of 1600×1200. The optris PI160 thermal camera has an image resolution of 160×120 pixels and a thermal resolution of 0.1° C. It acquires images with an accuracy of 2° C. The laser scanner acquires data with a field of view of $100^\circ \times 360^\circ$. To achieve the full horizontal field of view the scanner head rotates around the vertical scanner axis when acquiring the data. We take advantage of this feature when acquiring image data. Since the cameras are mounted on top of the scanner, they are also rotated. We acquire 9 images with each camera during one scanning process to cover the full 360°.

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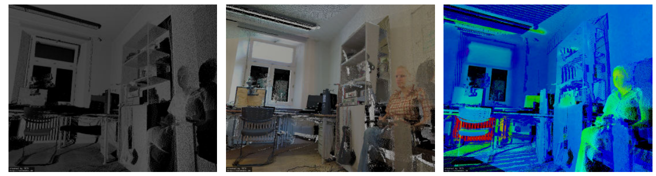

Fig. 1. Laser scan with reflectance, color and thermal information.

B. Data processing procedure

After acquiring the 3D data it has to be merged with the color information. This processing consists of five steps:

1) Intrinsic calibration of thermal and optical cameras: Each sensor perceives the world in its own local coordinate system. To join the perceived information we need the specific parameters of these coordinate systems. Each camera has unique parameters, namely distortion coefficients and intrinsic parameters, that define how a point in world coordinates is projected onto the image plane.

To determine the parameters of optical cameras chessboard patterns are commonly used because the corners are reliably detectable in the images [6]. A number of images showing a chessboard pattern with known number and size of squares are recorded. In each image the internal corners of the pattern are detected and the known distance between those in world coordinates allows to formulate a linear least squares problem to solve for the calibration parameters.

For low resolution thermal cameras a chessboard pattern is more error-prone even after heating it with an infrared lamp. Instead a pattern with clearly defined heat sources such as small lightbulbs is suggested as it shows up nicely in thermal images thus enabling us to perform intrinsic calibration in the same way as for optical cameras. To detect the light bulbs in the thermal image a thresholding procedure is applied to create a binary image showing regions of high temperature. A further thresholding step discards effectively all regions that are two big or too small. If the remaining number of regions is equal to the number of lightbulbs in the pattern the regions are sorted according to the pattern.

2) Extrinsic calibration – cameras and laser scanner: After calculating the internal camera parameters we need to align the camera images with the scanner coordinate system, i.e., extrinsic calibration. The 3 rotation and 3 translation parameters, known as the extrinsic camera parameters, define the geometric relation between cameras and laser scanner. Once all the points are in the camera coordinate system the projection to the image is defined up to a factor.

Suppose there are n images of the calibration pattern and m planar points on the pattern considering the distortions as independent and identically distributed noise then the maximum likelihood estimate of the transformation between the scanner and camera coordinate system is obtained by minimizing a non-linear equation system [3].

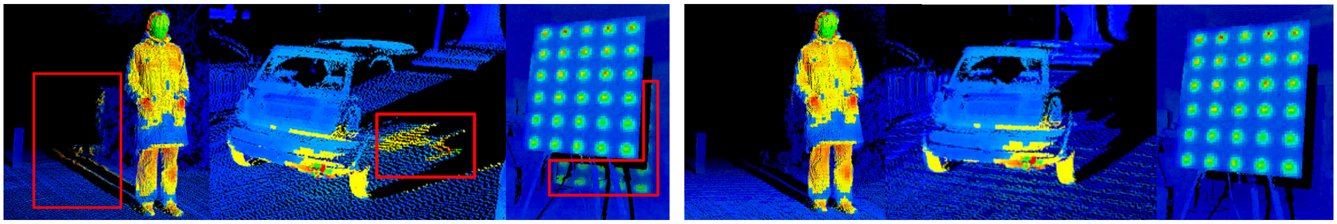

Fig. 2. Colored laser scan with errors (left) and with color correction (right).

This approach assumes a number of points identifiable in both the laser scan and the image. We attach the calibration pattern onto a board. For the optical camera this is a printed chessboard pattern and for the thermal camera light bulbs arranged in a regular grid pattern. The position of the points of these patterns are known. Algorithm 1 detects the points in a laser scan. An brief evaluation of the precision of the calibration process is given in [5].

Algorithm 1 Calibration pattern detection in a laser scan

Require: point cloud, specification of calibration pattern
1: discard points outside the area of the expected board
2: find the most prominent plane using RANSAC
3: project a generated plane model into the center of the detected plane
4: use ICP to fit the plane model to the data points
5: **return** position of the lightbulbs according to ICP result

3) 3D to 2D projection and color mapping: During the data acquisition phase laser scans and images are acquired simultaneously. After determining the relations between scanner and cameras in the calibration step this relation is used directly to color the point cloud according to the images.

4) Projection/occlusion/resolution errors: Due to the different fields of view the sensors see different parts of the world. An area that is visible for one sensor might be occluded for the other sensor. When mapping the color information to the point cloud this causes wrong correspondences and therefore faulty colored points. This impact is increased by the low resolution of the thermal camera. With only 120 by 160 pixels per image each pixel corresponds to many 3D points seen by the laser scanner leading to errors at jump edges. Consequently small calibration inaccuracies have a large impact on the results. To solve this problem we take advantage of the fact that if a point belongs to an object there will be more points on that object. We take all points that are projected onto one pixel and its neighboring pixels. The points are clustered depending on their distance to the scanner. A heuristic based on distance to the 3D scanner and size of the cluster determines effectively which points are considered and enhanced with color information.

This removes also some correct color information but the improvement prevails. Fig. 2 demonstrates this procedure. On the left show are the original colored point clouds. The red boxes mark areas with faulty colored points. The procedure eliminates these as seen on the right.

5) Low resolution cameras: Approaches commonly used when combining laser scan data and optical images use expensive high resolution cameras. We used a simple webcam in our experiments. However, the resolution of the thermal camera was only 120×160 pixels. This suggests that the approach is also applicable for low resolution optical cameras. To verify this we created an image pyramid of the optical images to compare the results achieved with different resolutions. Experiments showed that internal and external calibration could successfully be performed for all resolutions given careful positioning of the calibration pattern during calibration. Distances between 50 and 100 cm were large enough to capture the entire board reliably with the scanner and the pattern was still detectable in the camera images. Looking at results achieved with different resolution images shows that the quality decreases and error-proneness increases with decreasing resolution. This effect is diminished by smart application of the error correction algorithm depending on the scenario. In outdoor scenes where most objects are far away from the sensors the occlusion problem is small. The resolution problem discovered for the thermal camera is obviously smaller with higher resolution images. Accordingly the improvement achieved with the error correction algorithm here is smaller than the risk of omitting valuable information, e.g., at trees where a lot of overlap exists. Applying the correction algorithm with varying thresholds for decreasing resolution improves the results. Even at resolutions as low as 120×160 an outdoor scene benefits from the added color information.

6) Scan Registration: Laser scans acquired at different positions are registered into one common coordinate system using 6D SLAM from *The 3D Toolkit* (3DTK) [1]. The complete environment model can be inspected in the viewer from 3DTK enhanced with either reflectance values, thermal data or color from photos. Switching between the different views enables the user to detect sources of wasted energy and to locate them clearly in the more realistic optical view. Object recognition algorithms are applicable to identify heat sources in the optical data. Future work will concentrate on this aspect.

References

[1] Andreas Nüchter et al. 3DTK – The 3D Toolkit. `http://slam6d.sourceforge.net/`, August 2011.

[2] Andreas Nüchter et al. Project ThermalMapper. `http://www.faculty.jacobs-university.de/anuechter/thermalmapper.html`, August 2011.

[3] Gary Bradski and Adrian Kaehler. *Learning OpenCV, Computer Visoin with OpenCV library*. O'Reilly Media, first edition, 2008.

[4] Commission of the European Communities. Addressing the challenge of energy efficiency through Information and Communication Technologies. Communications from the Commisison to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, COM(2008) 241 final, May 2008.

[5] D. Borrmann, H. Afzal, J. Elseberg, and A. Nüchter. Mutual Calibration for 3D Thermal Mapping. In *Proc. of SYROCO 2012*. accepted.

[6] Zhengyou Zhang. Flexible camera calibration by viewing a plane from unknown orientations. In *in ICCV*, pages 666–673, 1999.