Sensor Fusion of a 2D Laser Scanner and a Thermal Camera

Johanna Gleichauf, Christian Pfitzner and Stefan May
Technische Hochschule Nürnberg Georg Simon Ohm, Kesslerplatz 12, Nuremberg, Germany

Keywords: Sensor Fusion, Calibration, 2D Laser Scanner, Thermal Camera.

Abstract: In order to increase the robustness of localisation and victim detection in low visibility situations it is necessary to fuse several sensors. The most common sensor used in robotics is the 2D laser scanner which delivers distance measurements. In combination with a camera the gained information can be supported by visual information about the environment. Thermal cameras are ideal for finding objects with a certain temperature, but they do not deliver distance information. The difficulty in fusing these two sensors is, that a correspondence between each distance measurement and its corresponding pixel within the thermal image needs to be found. As the laser scanner only displays one plane, this is not an intuitive task. A special triangular calibration target, covering all six degrees of freedom and being visible for both sensors, was developed. In the end the transformation between each laser scan point and its corresponding thermal image pixel is given. This allows for assigning every laser measurement within the field of view a corresponding thermal pixel. The final application will enable detection of human beings and display the distance required to reach them.

1 INTRODUCTION

For allowing robust localisation and victim detection sensor fusion of several sensors with different properties is needed. As the aim is to find possible victims in for example environments with great smoke emission, sensors applicable for this situation are required. The proposed sensor fusion system is made up of a thermal camera, a Short Wave Infrared (SWIR) camera, a laser scanner and a radar sensor. Laser scanners have limits in poor visibility situations. That is why radar sensors are a robust alternative.

So far a laser scanner and a thermal camera are used on the rescue robot Schroedi. In a fire drill with the firefighters in Nuremberg, Germany, it was demonstrated how victims could be found with the help of Schroedi (see Figure 1). At present, Schroedi can be steered into a room filled with smoke by a human and the victim detection is based on the operator's perception of the thermal images. For a human the detection of victims within an image is intuitive. If a robot had to detect the exact position and orientation of a possible victim, the operation becomes more complicated.

As part of a stationary test, sensor data was taken with a laser scanner, a thermal camera and a SWIR camera. The result is displayed within Figure 2 showing a human sitting within a room. A human is capable of identifying the human's position within the map (red circle) by eye. The robot needs to be taught to automatically combine the different data types and understand the information.

Figure 1: Rescue robot Schroedi at a fire drill (Source: A. Bergmeister).

The aim of this project is to implement the first part of the sensor fusion system, fusing a thermal camera with a laser scanner. Later on the laser scanner can be replaced by a radar sensor such that a robot is capable of detecting victims in a poor visibility situation such as a house fire. This requires the calibration of the thermal camera with a 2D laser scanner. The difficulty is that distance data (3D data) has to be projected onto the 2D image plane of the thermal camera image.

This paper is structured as follows: section 2 introduces existing calibration methods, section 3 de-

Gleichauf, J., Pfitzner, C. and May, S.
Sensor Fusion of a 2D Laser Scanner and a Thermal Camera.
DOI: 10.5220/0006397303980405
In *Proceedings of the 14th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2017) - Volume 1*, pages 398-405
ISBN: 978-989-758-263-9

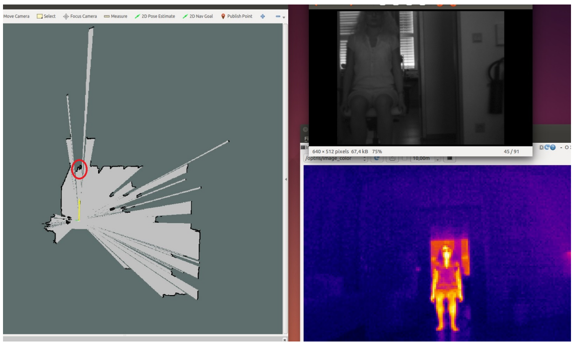

Figure 2: Laser scan map, thermal and SWIR image.

scribes the new approach and finally the conclusion and future work can be found in chapter 4.

2 STATE OF THE ART

Sensor fusion between several sensors is popular in robotics. Approaches of fusing a laser scanner with a thermal camera to combine the advantages of distance measurements and image information have been made. Most of these methods use a 3D laser scanner instead of a 2D one. Approaches combining an RGB camera with a 2D laser scanner are mentioned in this chapter, too, as the underlying method would be similar for an infrared camera.

2.1 Fusion of a Thermal Camera with a 3D Laser Scanner

In his Bachelor thesis Tom-Marvin Liebelt describes the sensor fusion between a 3D laser scanner (a rotated SICK LMS100 2D scanner) and a thermal camera. Both sensors are placed in a fixed position such that the z-axis of the camera lies on the scan plane of the laser scanner. Different types of calibration patterns (a printed pattern, a pattern using light bulbs and one using resistance wire) were compared in this project. It was decided to use resistance wire which delivers good thermal images and allows the resulting pattern to be used for both the intrinsic and extrinsic calibration. (Liebelt, 2013)

As part of the Smokebot project the calibration and fusion between a far infrared camera and a 3D laser scanner were performed. Their calibration pattern is of trihedral shape such that its edges can be clearly seen within the laser point cloud. (Zeise, 2016)

2.2 Fusion of a Thermal Camera with a 2D Laser Scanner

An approach using an infrared camera is used for fast moving object detection. The extrinsic calibration between the two sensors is not precise. Zeng et al. (2015) approximated the extrinsic transformation by finding agreement between the horizontal axes. The difference in the vertical axis (i.e., z) was then measured manually. For their project this low precision calibration was sufficient to be able to locate the Region of Interest (ROI).

2.3 Fusion of a Camera with a 3D Laser Scanner

Several fusion applications can be found using different types of cameras and a 3D laser scanner. Unnikrishnan et al. (2005) introduce the usage of a Laser-Camera Calibration Toolbox, based on a Matlab graphical user interface. Their calibration pattern is a leaning chessboard.

For mapping infrared data onto a terrestrial laser scanner for 3D models of buildings a ”bi-camera” system made up of a thermal camera and a RGB camera was created. The aim is to overcome drawbacks such as time consuming methods caused by classic approaches where direct registration between the thermal camera and the 3D laser scanner is taking place using space resection or homography. Furthermore a low-cost NIR camera is integrated into the system. For the calibration between the ”bi-camera” system and the 3D laser scanner, the recognition of common features between RGB images and the laser intensity is suggested as in (Meierhold et al., 2010) (this is a manual task if no targets are used). (Alba et al., 2011)

A similar work was proposed by Borrmann et al. (2013) with the exceptions that calibration patterns are used, a printed chessboard pattern for the optical camera and attached lightbulbs for the infrared camera. The position of the points within these patterns needs to be detected within the laser scan.

An arbitrary trihedron can be used as calibration pattern, too. The calibration is based on a non linear least square problem formulated in terms of geometric constraints. (Gong et al., 2013)

Pandey et al. (2010) fuse a 3D laser scanner with an omnidirectional camera. Their calibration method is based on the approach introduced by Zhang (see below), with the difference of using an omnidirectional camera instead of a classical camera. A planar checkerboard pattern is required and needs to be observed from both, the laser scanner and the camera system from at least three points of view.

2.4 Extrinsic Calibration of a Camera with a 2D Laser Scanner

Within the research area of pedestrian detection a 2D laser scanner and a Far Infrared camera are fused. The calibration is based on the least mean square (LMS) algorithm. This algorithm takes a sample sequence with a single pedestrian such that the person can be detected within both sensor modalities. The coefficients to convert the coordinates from the camera to the laser scanner coordinate system is calculated. (Garcia et al., 2010)

Alternatively there are approaches fusing a standard camera with a 2D laser scanner using different calibration patterns.

Wasilewsky and Strauss use a rectangular folded target with one side being black and the other one coloured white. This allows a clear differentiation between the two halfs using the camera. The laser scanner produces a triangular scan line - two lines intersecting in one point. Hereby the point of intersection is clearly visible within the laser scan and the camera image. (Wasielewski and Strauss, 1995)

Zhang and Pless propose a calibration using a simple checkerboard and solve all geometric constraints for the transformation under the assumption that the laser scan points must lie on the camera (calibration) plane (Zhang and Pless, 2004). This method is implemented within the automatic matlab tool by Kassir and Peynot (Kassir and Peynot, 2010).

A further approach uses a black line on a white sheet as calibration target. A created polynomial system is solved and the laserscan point which is normal to the plane is derived (Naroditsky et al., 2011).

Most of the suggested calibration methods for 2D laser scanners have disadvantages due to a lack of degrees of freedom. Six degrees of freedom (translation in X, Y and Z direction and rotation around these axes) are necessary to exactly determine the extrinsic transformation.

As described by Dong and Isler for the methods suggested by Zhang (Zhang and Pless, 2004), Wasielewski (Wasielewski and Strauss, 1995) and Naroditsky (Naroditsky et al., 2011) there are missing degrees of freedom (Dong and Isler, 2016). This means that either turning or shifting the calibration target in different directions would still deliver the same scan points or line even though it has a completely different position and it should be possible to distinguish between the scans.

Dong and Isler developed a calibration target made up of two triangles which are positioned at an angle of 150° to each other. Using this target for calibration, all six degrees of freedom are covered. A complex algorithm using different planes and vectors solves all constraints for the extrinsic transformation. (Dong and Isler, 2016)

This overview showed that no precise extrinsic calibration method exists for the fusion of a 2D laser scanner and a thermal camera. Therefore a new method has to be introduced. Due to the fact that the calibration pattern proposed by Dong and Isler covers all degrees of freedom it was decided to use a similar calibration target with the difference that it must be visible for the thermal camera instead of a RGB camera. This new approach also uses a third sensor to help with the fusion.

3 APPROACH

The chosen approach will be described in detail in this chapter. The laser scanner and the thermal camera are combined with a NoIR camera.

3.1 Sensor Set Up

Both sensors are fixed on top of each other (see Figure 3). This is necessary to stop a parallax error occuring. Otherwise the sensors would 'look' sideways onto each other which leads to an ambiguity. A NoIR camera is fixed on top of the thermal camera to help with the calibration and is removed afterwards.

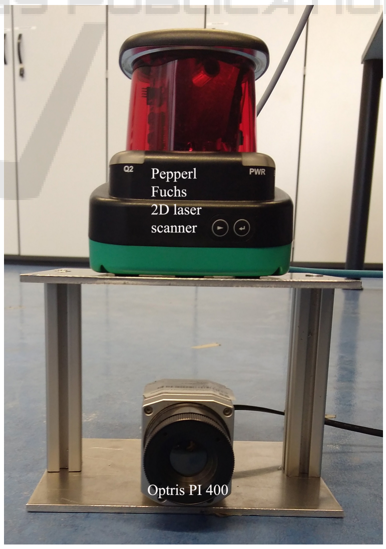

Figure 3: Sensor set up.

The 2D laser scanner in use is the R2000 ODM30M designed by the company Pepperl und Fuchs. It has a wavelength of 905 nm, a resolution of 1 mm and an angular resolution of 0,014°. The

ROS package *pepperl_fuchs_r2000* supplies a driver for this type of laser scanner. In this project a scan rate of 50 Hz and 3600 scan samples was chosen. The laser scanner delivers range and intensity data of the measurements 360° around itself.

The thermal camera in use is the Optris PI 400. It has an uncooled detector and delivers a temperature sensitivity of up to 0.8 K. Its spectral range lies between 7.5 and 13μm. The ROS package *optris_drivers* is used as interface for the camera.

Additionaly to the main sensors a Raspberry Pi camera is applied to help with the calibration between the laser scanner and the thermal camera. Further details can be found in the later chapters. The No Infrared (NoIR) camera (camera module v1) is connected to a Raspberry Pi computer. NoIR implies the lack of an infrared filter such that infrared light can be detected. This camera is capable of seeing the laser scan line. The Raspberry Pi runs with the 16.04 Ubuntu mate version. The ROS package *raspicam* is the driver used to run the camera.

3.2 Intrinsic Calibration of the Thermal and the NoIR Camera

The ROS package *camera_calibration* is used for the intrinsic calibration of both the thermal camera and the NoIR camera. The intrinsic calibration is necessary to rectify the image and to remove distortions. It relates to the projection of the chip plane onto the image plane of the camera sensor such that the transformation between the sensor's pixel coordinates and the world coordinate frame is given. Both cameras can be modelled as a pinhole camera represented by this formula:

$$\begin{pmatrix} u \\ v \\ 1 \end{pmatrix} = \begin{pmatrix} f_x & 0 & u_0 \\ 0 & f_y & v_0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} X/Z \\ Y/Z \\ 1 \end{pmatrix}$$

where (u,v) are the distorted image coordinates, f_x and f_y are the focal length, u_0 and v_0 are the coordinates of the center of the camera sensor. X, Y and Z make up the 3D coordinate within the world coordinate system.

Images of the heated calibration pattern with 9x6 circles with a distance to each other of 3.75 cm are computed by the calibration tool. The images need to be taken from all different orientations, distances and at varying degrees of skewness so that the tangential and radial distortion coefficients can be precisely calculated. The distortions are removed by applying the following formula to the pixel coordinates:

$$\begin{pmatrix} u'' \\ v'' \end{pmatrix} = \begin{pmatrix} u' \cdot k + 2p_1 v' + p_2 \cdot (r^2 + 2u'^2) \\ v' \cdot k + 2p_1 \cdot (r^2 + 2v'^2) + p_2 u' \end{pmatrix}$$

with

$$k = (1 + k_1 r^2 + k_2 r^4 + k_3 r^6)$$

where k_1, k_2 and k_3 are the radial distortion coefficients and p_1 and p_2 are the tangential distortion coefficients. r is the Euclidean distance of u' and v' with $u' = u - u_0$ and $v' = v - v_0$.
The camera matrix and the distortion factors are saved within a yaml file which is called by the camera driver when starting it.

The same calibration target has a black and white pattern on its backside which delivers a good contrast for the calibration of the Raspberry Pi camera. The calibration package *camera_calibration* was installed and run on the Raspberry Pi itself. The calibration procedure is the same as for the thermal camera.

3.3 Extrinsic Calibration

A special calibration target was developed for the extrinsic calibration of the laser scanner and the thermal camera (see Figure 4 left).
The basic principle is based upon the publication of Dong and Isler (Dong and Isler, 2016). In their paper they describe the extrinsic calibration of a camera and a 2D laser scanner. Their approach allows a direct calibration covering all six degrees of freedom. In their paper two triangles are positioned to each other at an angle of 150°. When using a thermal camera instead of an RGB camera the target needs to be heated so that a clear temperature gradient can be detected. For this reason two triangular shaped aluminium plates were produced. As only the edges of the triangle are of major interest, two slightly smaller triangles made of high density fibreboard (HDF), are placed in front. The whole calibration target is fixed on a wooden board so that it remains in an angle of 150°, with the two triangles being connected by a metal hinge.

The first test to check whether useful images and sensor data can be generated was done by heating the target with a hot air blower. The calibration target was clearly visible in all different sensor images. Surprisingly the edges of the aluminium triangles were not visible within the thermal image. It became apparent that the aluminium cools down much faster than the HDF boards so that the whole wooden plane was actually visible within the thermal image (see Figure 4 middle). For this reason the calibration target had to be adjusted. So far the aluminium was forming the edges of the triangular target. As the aluminium is not visible, the wooden triangles were moved towards the middle, so that the middle edge is visible.

In order to calculate the extrinsic transformation including translation and rotation between one laser

Figure 4: Special calibration target (le.), Calibration target within thermal camera image (mid.) and Laser scan line within NoIR image (ri.).

scan point and one thermal image pixel, the following steps had to be followed.

The intersection points between the scan line and the edges of the triangle need to be identified in both the laser scan data and the thermal camera image. The laser scan data needs to be filtered so that only the scan points displaying the calibration target remain. Furthermore reflections caused by the laser scan line interfering with the target's edges need to be removed. The scan points belonging to the calibration target's edges need to be detected. The Raspberry Pi camera without an infrared filter, helps to detect the actual laser scan line (see Figure 4 right). First the transformation between the NoIR image and the thermal camera image needs to be calculated using the triangle corner coordinates within both images. The next step is to find the corresponding pixels within the thermal image by applying the transformation on the intersection points within the NoIR image such that they are given within the thermal camera image. Once the scan points and the thermal image points of the intersection are known, they need to be inserted into an algorithm which calculates the extrinsic transformation out of them. The used function is the *SolvePnP* function by OpenCV.

3.3.1 Laser Data

The laser scan data holds all measurements which are placed 360° around the scanner with a maximum range of 100 m. For the calibration only measurements corresponding to the calibration target are required - the triangular line within Figure 5 - that is why filtering is needed. The colourful axes represent the laser scanner.
Only angles between -31 and 31° within the laser scan data are accepted. This is because the thermal camera only has a field of view of 62°. A distance filter is applied, too, such that all distances further and closer than the calibration target are eliminated. Artefacts caused by reflections at the edges of the object are filtered out by comparing the distances to the neighbours. If they exceed a threshold value, the laser scan is set to "not a number". Additionally only scans of a certain intensity are accepted. The laser scans

Figure 5: Relevant laser data.

are furthermore converted to 3D-coordinates as the *solvePnP* function needs the *objectPoints* in this format. As last step the search for the edge scan points is implemented so that the relevant values are returned. The edge point in the middle is the laser scan value with the greatest distance, if the target is positioned such as within Figure 5. The outer intersection points are the first and the last point within the scan.

3.3.2 Raspberry PI Camera Data

The pixel coordinates of the wooden triangles need to be found within both the Raspberry Pi camera image and the thermal camera image. As the NoIR image was taken in complete darkness so that the laser scan line appears brighter, histogram equalisation is necessary.

First of all image processing methods were considered to segment the laser scan line within the image. The image was supposed to be binarised at first after which an appropriate threshold was to be found so only the scan line remains. As the laser scan line is broad due to the distance from which the image was taken this was not possible. So even when applying the Canny operator to detect the edges or different implementations of a thinning algorithm by Zhang and Suen, no suitable result was gained. Another option would be the Hough Transform which detects lines within images. Unfortunately the laser scan line is not a constant line because of the laser cut holes within the calibration target so that none of the mentioned approaches led to satisfying extraction.

In the end it was decided to determine the coordinates of the (wooden) triangle corners as well as the intersection points with the laser scan line manually using OpenCV3. The triangle corner coordinates were found within the thermal camera image and the NoIR image. One frame of the recorded bagfile is used and by drawing in lines around the triangular shape and through the middle of the laser scan line the significant points are determined and the correctness is checked at the same time. The intersection points with the laser scan line were determined within the NoIR image, too. The triangle corner coordinates within both images were used to calculate the transformation between them.

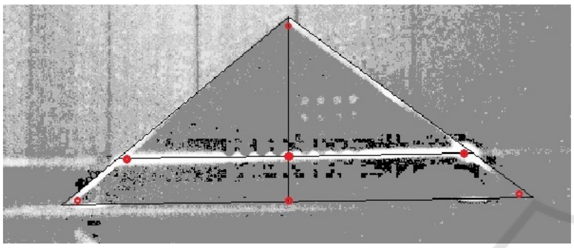

Figure 6: Points selected within the NoIR image.

Four points from both modalities were first selected and inserted into the function OpenCV *findHomography* . This function is supposed to deliver the transformation between the thermal and Raspberry Pi camera image pixels. Unfortunately this function returned an incorrect transformation matrix so an alternative function was required. The OpenCV function *getAffineTransform* fulfills this task. This transformation was applied on the intersection points (*transform*) such that they are known within the thermal camera image. To gain more accuracy this was done for the two subtriangles halfs seperately as they correspond to two different planes.

3.3.3 Calculation of the Extrinsic Transformation Matrix

To be able to finally calculate the extrinsic transformation between the laser scanner and the thermal camera, the laser 3D coordinates and the correspondig pixel values within the thermal image are both processed by the *solvePnP* function which returns the rotation and the translation as 3x1 vectors.

SolvePnP. Using several corresponding laser and thermal points, the extrinsic transformation is calculated using the function *solvePnP* from OpenCV. This implementation is based on the publication by Zhang (Zhang, 2000).
The function estimates the object pose given a set of 3D laser points (object points) and their corresponding thermal pixels (image projections), taking the camera matrix and the distortion coefficients into account. If the points lie on the same plane it internally calls the function *findHomography* which finds the perspective transform between two planes, and refines it by applying Levenberg-Marquardt approximation, which is an optimisation algorithm based on the least squares method. If the points lie on different planes the Direct Linear Transform (DLT) algorithm is used. It calculates the matrix A which projects the 3D laser points (y_1, y_2, y_3) onto the thermal 2D plane (x_1, x_2) such that:

$$\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{pmatrix} \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix}$$

The function *solvePnP* returns the required rotational and translational vectors which represent the extrinsic transformation.
In order to apply this transformation on all laserpoints a reprojection has to take place. This was done manually at first. In order to get a 4x4 matrix which can be applied on each laser point coordinate, a rotation matrix was formed using the Rodrigues function. This function returns a 3x3 rotation matrix. (Rodrigues, 2017) The transformed laser points within the thermal image have the unit m. The conversion to the pixel value coordinates is done by taking the field of view (FOV) of the thermal camera into account. The FOV in the x-direction is of 62°, into the y-direction the FOV is of 49°. The width and height of the image in meters depends on the distance the image was taken from. It turned out that this method lead to erroneous values so that the more precise function *projectPoints* was used instead. This function projects 3D points onto the image plane.

The transformation is applied to all laserpoints and projected into the thermal camera image. The aim is to display the human's temperature and the distance to them. The first approach was to find the most common temperature of the laser scan line and get the corresponding average distance. Only temperatures within the human's skin temperature range are of interest.

Results. The relevant temperature range is made flexible by finding the maximum temperature value of the laser scan line. The minimum value is set as the maximum - 3 °C ($t_{min} = t_{max} - 3$°C).

The distance found is now the minimum distance as the closest person has to be found first. This automatically filters out too large values.

The sensors have to be positioned on top of each other so that no parallax error can occur (see Figure 3). If the sensors were positioned next to each other they would have different field of views. This leads to the effect that the thermal camera is looking sideways onto the laser scan measurements. The parallax error has an impact on the short but not long distances. The results, if the sensors are placed on top of each other, for the closest values as well as the further ones are then accurate.

It was also found out that the thermal emission of the body leads to the effect that the thermal camera detects pixels with the same temperature even though they are not part of the body and the laser scanner returns too long distances. These values need to be filtered out.

Additionally it has to be made sure that a distance of at least 35 cm is kept to the sensor system. Otherwise the laser scan line is not within the measurement field of the thermal camera. The camera's optic has to be taken into account. Half the height of the measurement field has to be greater than the distance between the laser scanner and the thermal camera in vertical direction (about 16 cm). Using the optic's calculator by optris this leads to a minimum distance of 35 cm.

As final test a person was positioned with different distances to the sensor system and the distance was measured with a reference laser measurement and with the sensor system. The reference measurement had an accuracy of 1-2 cm. The data is visualised within a Bland-Altman plot and shows that with the exceptance of one outlier the accuracy of the sensor fusion system is high (see Figure 7).

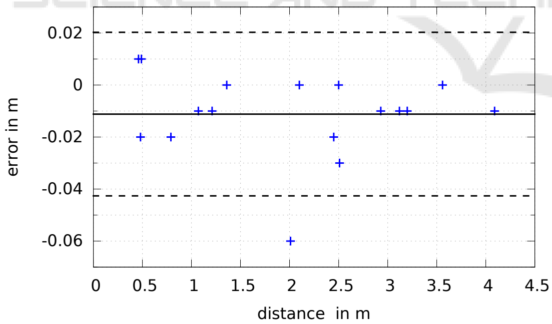

Figure 7: Bland-Altman plot.

The following images present the results of the sensor fusion system.

It was found out that the greater the distance the more inacurrate the calibration. This is due to the resolution of the thermal camera. Distances up to 10 m can be determined with great accuracy. For the intended aim this distance is sufficient as a flat should not have greater dimensions.

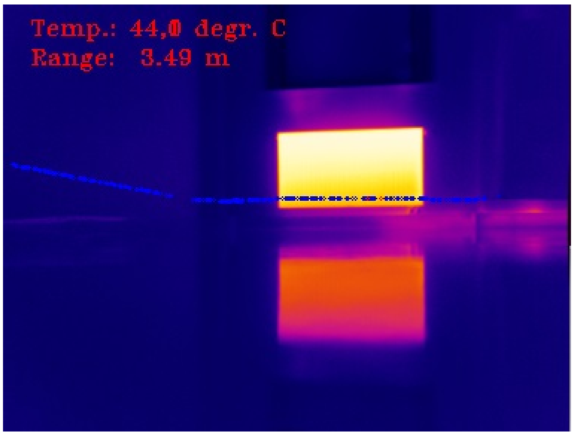

Figure 8: Temperature and distance to a radiator.

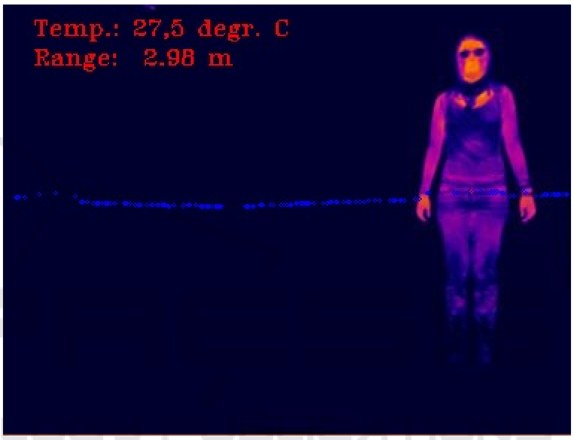

Figure 9: Human with a distance of about 3 m.

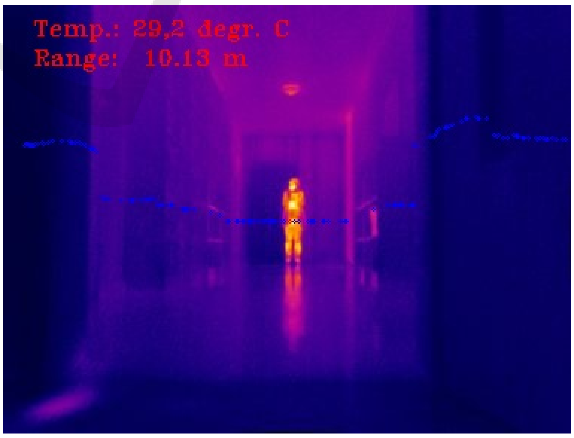

Figure 10: Human with a distance of about 10 m.

4 CONCLUSIONS

It was shown that it is possible to fuse a 2D laser scanner with a thermal camera using a special triangular calibration target and a NoIR camera to help. This new calibration method covers all six degrees of freedom. The sensor set up has to be such that the sensors are placed on top of each other so that no parallax error occurs. Furthermore a distance greater than 35 cm has to be kept to the sensor system. Otherwise the laser scan line does not lie within the thermal camera measurement field. It was verified that this system works for distances up to 10 m (see Figure 10).

In the future this system can be improved by using a thermal camera with a higher resolution. This will make it applicable for greater distances. Additionally it can be considered to use image processing and object detection algorithms for detecting more than one person within the image at a time. Furthermore the existing system can be expanded by a SWIR camera and a radar sensor to allow localisation under poor visibility conditions.

REFERENCES

Alba, M. I., Barazzetti, L., Scaioni, M., Rosina, E., and Previtali, M. (2011). Mapping infrared data on terrestrial laser scanning 3d models of buildings. *Remote Sensing*, 3(9):1847.

Borrmann, D., Elseberg, J., and Nüchter, A. (2013). *Thermal 3D Mapping of Building Façades*, pages 173–182. Springer Berlin Heidelberg, Berlin, Heidelberg.

Dong, W. and Isler, V. (2016). A novel method for extrinsic calibration of a 2-d laser-rangefinder and a camera. *CoRR*, abs/1603.04132.

Garcia, F., Olmeda, D., Armingol, J., and de la Escalera, A. (2010). Hybrid fusion schemer for pedestrian detection based on laser scanner and far infrared camera. In *Proceedings of 2010 IEEE Intelligent Vehicles Symposium, San Diego, USA*.

Gong, X., Lin, Y., and Liu, J. (2013). 3d lidar-camera extrinsic calibration using an arbitrary trihedron. *Sensors*, 13(2):1902.

Kassir, A. and Peynot, T. (2010). Reliable automatic camera-laser calibration. In *Proceedings of Australasian Conference on Robotics and Automation, Brisbane, Australia*.

Liebelt, T.-M. (2013). Fusion von 3D-Laserscanner-Daten mit 2D Thermal-Bilddaten. Bachelor thesis, Westfälische Hochschule Gelsenkirchen.

Meierhold, N., Spehr, M., Schilling, A., Gumhold, S., and Maas, H. (2010). Automatic feature matching between digital images and 2d representations of a 3d laser scanner point cloud. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Science, Newcastle upon Tyne, UK*, 38:446–451.

Naroditsky, O., Patterson, A., and Daniilidis, K. (2011). Automatic alignment of a camera with a line scan lidar system. In *Proceedings of 2011 IEEE International Conference on Robotics and Automation (ICRA), Shanghai, China*, pages 3429–3434.

Pandey, G., McBride, J., Savarese, S., and Eustice, R. (2010). Extrinsic calibration of a 3d laser scanner and an omnidirectional camera. *IFAC Proceedings Volumes, Lecce, Italy*, 43(16):336 – 341.

Rodrigues (2017). Rodrigus. http://docs.opencv.org/2.4/modules/calib3d/doc/camera_calibration_and_3d_reconstruction.html#rodrigues. Accessed on 04 May 2017.

Unnikrishnan, R. and Hebert, M. (2005). Fast extrinsic calibration of a laser rangefinder to a camera. Technical Report CMU-RI-TR-05-09, Robotics Institute, Pittsburgh, PA.

Wagner, M., Heß, P., Reitelshöfer, S., and Franke, J. (2015). Data fusion between a 2d laser profile sensor and a camera. In *Proceedings of 12th International Conference on Informatics in Control, Automation and Robotics (ICINCO), 2015, Colmar, Alsace, France*, volume 02, pages 159–165.

Wasielewski, S. and Strauss, O. (1995). Calibration of a multi-sensor system laser rangefinder / camera. In *Proceedings of the IEEE Xplore Conference: Intelligent Vehicles '95 Symposium., Detroit, USA*.

Zeise, B. (2016). Smokebot deliverable 3.2: Software toolkit indoor surface temperature mapping. http://aass.oru.se/Research/mro/smokebot/deliverables/SmokeBot_D3_2.pdf. Accessed on 14 November 2016.

Zeng, L., Ding, M., Zhang, T., and Sun, Z. (2015). A fast moving object detection method based on 2d laser scanner and infrared camera. In *Proceedings of SPIE 9675, AOPC 2015: Image Processing and Analysis, Beijing, China*.

Zhang, Q. and Pless, R. (2004). Extrinsic calibration of a camera and laser range finder (improves camera calibration). In *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, 2004. (IROS 2004), Sendai, Japan*.

Zhang, Z. (2000). A flexible new technique for camera calibration. In *Proceedings of IEEE Transactions on Pattern Analysis and Machine Intelligence*, volume 22, page 13301334.