Mobile Robot Self Localization and 3D Map Building using a 3D PMD-Camera for tele-robotic applications

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Abstract: This work purpose using a 3D PMD camera as a sensor for mobile robot applications. The use of image sensors for environment detection is substantial and common usage in mobile robot exploration. Laser scanners, 3D stereo vision or a combination of them are be used generally. The PMD camera is a novel 3D measuring system, which is based on a time-of-flight principle. The main feature is an array sensor, which can measure the distance to the target without scanning. This relatively new technology offers a cost-effective alternative to the mentioned sensors. In the following we present methods for self-localization and 3D map building by remote sensor data acquisition. This allows the teleoperative control of a mobile robot in an unknown environment. To enhance the mobile robot tasks, a CCD and the PMD camera are registered in order to create the three dimensional mapping. The CCD texture data will be overlaid with the PMD depth data to increase the accuracy of the lateral resolution. The visual input from the CCD camera not only delivers high resolution texture data, it can also apply for object recognition in clutter environment.

Keywords: PMD camera, sensor and data fusion, remote sensor data acquisition, mobile robots, telerobotics, self localization, 3D map building.

1. INTRODUCTION

In the following article methods with the objective of integration of the PMD (photonic mixer device) technology in teleoperative robotic applications for 3D mapping will be presented. Because of this the PMD functional principle and the used robot system will be introduced to the reader at first. To generate a 3D environment map with a 3D vision system mounted at a robot, it is important to know the exact robot position and orientation. On this account we will go into methods for precise self localization. The self localization methods combines informations getting from the wheel encoders of the robot with position data calculated from the PMD data. If the self localization is realized, the recording of a coloured 3D map will be discussed. Moreover, the enhancing 3D scenario by combination 2D/PMD camera will be presented. The combination data can provide not only the depth data from PMD but also provide the contour with depth data. This data can easily adapt to use in 3D geometry application.

1.1 3D PMD-Camera System

The PMD (photonic mixer device) camera offers a cost effective alternative to other 2D or 3D measuring systems like stereo vision systems or laserscanners in mobile robot applications. The camera provides to measure distance values of a scene for each pixel. The functional principle of the camera bases on a "time-of-flight" measuring system.

An illumination module sends out rectangular modulated light in the range of near infrared (wavelength l = 870nm). The Sensor receives the reflected light and mixes it with a reference signal, like it is shown in fig.1. The reference signal has the same modulation frequency $f_{mod}$ as the received light. Using a phase shift method an auto correlation function between both signals, the received light and the reference signal can be built. The maximum of this function is an admasurement for the phase shift $\phi$, it depends on the distance of the light to the object and back. The resulting distance $d$ can be calculated by:

$$d = \frac{c \cdot \phi}{4\pi \cdot f_{mod}}$$

(1)

with the light velocity $c$. 

Fig. 1. Functional principle of a PMD-Camera
The camera facilitates to get a 3D image of the scene with a framerate of 20 images per second. For the following applications we used a [PMDVision]S3 camera of the company PMDTec with a lateral resolution of 64x48 pixel. The accuracy of the distance measurement of the choosen camera depends on the reflectivity of the object and can be adjusted to the scene by changing the integration time of the camera. The maximum achievable accuracy amounts only a few millimeter. The integration time is equal to the illumination time of a conventional camera and it is the time the system needs for one phase measurement. The measuring range of the camera is $d_{\text{max}} = 7.5m$ and depends on the modulation frequency $f_{\text{mod}}$ of the camera. For more informations about PMD technology we refer to Ringbeck (2007)

### 1.2 Robot System

![Fig. 2. Setup of the mobile robot](image)

Fig. 2 shows the setup of the mobile robot. As the basis of the robot system serves a electro scooter. This scooter is featured with a path controlling unit, a steering motor and wheel encoder to get the functionality of a mobile robot. For self localization, and 3D map building during the teleoperative control of the robot, it is equipped with a [PMDVision]S3 camera which observes the area in the front of the robot.

### 2. ROBOT-CAMERA CALIBRATION

To use the PMD camera mounted at the robot it is necessary to know the transformation matrix $R_{\text{Rob}}T_{\text{Cam}}$ between robot and camera coordinate system. Only with this information it is possible to fuse both data which is essential for PMD assisted self localization and map building. Because the position of the camera at the robot is fixed it can measured at the mechanic installation. But the orientation can be variagated by the user. Because of different reflectivities of the floor and the measurement range of the camera it is advisable to adjust the inclination angle of the camera. Here a automatic calibration algorithm is needful. To calculate the rotational part

$$R_{\text{Rob}}^R = R_{\text{Cam}}^C \times R_{\text{Cam}}^C$$

(2)

of the transformation matrix the direction vectors of the robot system must be specified with the PMD camera. For this the minimum of two vectors have to be determined. $R_{\text{Cam}}^C$ equates to the normal vector of the plane recorded by the PMD camera which represent the floor.

![Fig. 3. Calculation of the z-vector of the robot coordination system](image)

Fig. 3 shows the plane and the normal vector calculated by the measuring of the floor position using the PMD camera. The second step to calculate the transformation matrix is the determination of the x position. This is possible by moving the robot with a steering angle of zero in forward direction. During the robot motion a fixed object in front of the robot must be recognized and its position must be calculated.

![Fig. 4. Calculation of the x-vector of the robot coordination system](image)

The principle of this calibration movement is shown in fig. 4. Using the equation:

$$y_{\text{Rob}} = z_{\text{Rob}} \times x_{\text{Rob}}$$

(3)

the rotational part can calculated completely.

### 3. SELF LOCALIZATION

The robot combines the possibility of self localization using the wheel encoder and the localization using the PMD camera. The localization with the wheel encoder is a well known method. Here we want to refer to the appropriate literature. Using the PMD camera to localize the robot position offers two possibilities. In this section we describe two different options. The first option is the localization with the recognition of artificial landmarks with a known position in the robot environment. The second possibility is a relative position localization method. Using the ICP algorithm facilitates the calculation of moving vectors between the recorded images.

#### 3.1 Absolute Position Localization with Artificial Landmarks

The absolute position localization serves on the one hand to calculate the start position of the robot. On the other hand it offers to adjust mismeasurements of the relative self localization methods.

![Fig. 5 shows the delineation to calculate the transformation matrix to adjust the robot position](image)

Fig.5 shows the delineation to calculate the transformation matrix to adjust the robot position. If the robot detects the landmark, the transformation matrix $R_{\text{Rob}}T_{\text{LM}}$ can be
The translational part of the transformation matrix is:
\[ t = c_m - R \cdot c_p \]  

The components correspond to the actual robot position and orientation can be calculated using equations 4 and 5 the transformation matrix to adjust the position of the landmark is:
\[ WCT_{LM_{measured}} = WCT_{Rob_{corr}}T_{Rob}^{T}T_{LM} \]  

To detect the artificial landmarks with the PMD camera the grayscale values given by the PMD sensor can be used. The detection occurs using the the Haar-Like-Feature method, developed by Viola and Jones (2001). To get a strong classifier for detecting the landmark in the PMD images, more than thousand positive images (images which include the landmark) and negative images (images which doesn’t include the landmark) nearly twice the number of positive images, are recorded.

Using the Canny algorithm for edge detection, the pixels at the transition between the black and white regions of the landmark can be marked. Like it is highlighted in Fig.7. Under consideration of the 3D values of the landmark and world coordinate system, which equates to the position and orientation of the landmark is:
\[ WCT_{LM_{measured}} = WCT_{Rob_{corr}}T_{Rob}^{T}T_{LM} \]  

The rotational part of the transformation matrix can be calculated using the SVD algorithm [Wall (2003)]. The SVD algorithm generates the correlation matrix \( H \) of the corresponding points.

The rotational part of the transformation matrix can be calculated using the ICP algorithm [P. J. Besl (1992)]. The ICP algorithm is a iterative algorithm, which allows the computation between two 3D point clouds. The algorithm consists of three steps. At first the next neighbour of each point \( p_i \) in the first \( P \) point cloud to the each point \( m_i \) in the second \( M \) point cloud will be calculated. With the minimization of the quadratic failure between the corresponding points the transformation matrix between the point clouds can be determined. The second step is to minimize the quadratic cost function:
\[ d(R, t) = \frac{1}{P_P} \sum_{i=1}^{N_P} \| m_i - R \cdot p_i + t \|^2 \]  

The matrix elements can calculated by:
\[ S_{xx} = \sum_{i=1}^{N_P} m_{ix} \cdot p_{ix} \]  
\[ S_{xy} = \sum_{i=1}^{N_P} m_{ix} \cdot p_{iy} \]  

Using the Haar-Like-Feature shown in fig.6 integral images of the recorded images can be calculated. With the help of the AdaBoost algorithm it is possible to get several weak classifiers which can be cascaded to a strong classifier. This can be used to recognize the landmark in the PMD images with 20 frames per second.

Fig.7 shows the result of the recognition algorithm. The landmark is indicated by a square. The position of the landmark is calculated but the orientation is still unknown. Using the Canny algorithm for edge detection, the pixels at the transition between the black and white regions of the landmark can be marked. Like it is highlighted in Fig.7. Under consideration of the 3D values of the landmark the orientation is still unknown.

\[ R = V \cdot U^T \]  

The rotation matrix \( R \) corresponds to
\[ H = U \Lambda V^T \]  

The translational part of the transformation matrix is:
\[ t = c_m - R \cdot c_p \]
$c_m$ and $c_p$ are the mean values of the corresponding point clouds. The third step is the registration of the calculated transformation matrix to the point clouds. This three steps will be iteratively used, till the number of maximum iteration is reached or the sum of the quadratic failures between the corresponding points is lower than a defined limit.

Fig. 8. Using the ICP algorithm to shift PMD images

Fig. 9. Using the ICP algorithm to shift the precalculated point clouds

With the precalculation and the use of a kd-tree search algorithm the calculation period can be decreased to $t = 60$ms, in the example shown in fig.9. Of course the time depends on the number of iterations and the number of the considered points during the calculation of the ICP algorithm.

3.3 Sensor Fusion

After different methods for self localization of the mobile robot are implemented a procedure to fuse the different measurements is needed. The aim is to get a more accurate measurement as using only one method.

At first both implemented relative position measuring methods must be fused. The fusion is displayed in fig.10. With the Kalman filter, developed from Kalman (1960), the failure between the wheel encoder data and the image vectors, calculated by the ICP algorithm, can be estimate. Considering this estimation the relative self localization can be corrected. If a landmark is detected it allows an inference to the real robot position and the assumed position can be corrected.

4. 2D/3D CAMERAS COMBINATION

4.1 Camera Combination

The depth data of the PMD camera provides good precise depth informations. But as a result of the low lateral resolution and the missing colour information, compared to normal CCD cameras, the recognition of objects in clutter environments is turned out to be difficulty. Indeed a precise object detection is fundamental for 3D mapping. The approach of the described problem is, that the excellent PMD depth data can be enhanced, if the depth information is fulfilled by color data from a CCD camera. The 2D/3D combination approach can provides enough information to handle the object detection problem in clutter scenario. The PMD data estimates the distance and contour information use for observing objects. The contour information can be used to identify the objects in the PMD camera coordinate system. The transformation of the three-dimensional coordinates enhances the system applicable in real time operation. Prasad et al. (2006) presented a fundamental approach of enhancement the 3D vision output. They placed the 2D and 3D camera in a special structure and assume the field of view of both cameras almost the same. The real 3D range information with high intensity was generated. Mischler (2007) reconstructed the 3D model of stereo and PMD data by using an OpenCV library. This paper uses the hardware setup principles and projective texture on geometry.

Fig. 10. Sensor fusion of absolute and relative self localization algorithms

Fig. 11. Camera calibration model

As Fig. 11 denotes that $(Q_x, Q_y, Q_z)$ are coordinates of point $Q$ in the world space. Assume the object was pointed out by the CCD camera, $q(q_a, q_b)$ is the projected coordinate onto an artificial camera frame, if the original of
the image coordinate does not align on Z image plan axis. Denote \((a_0, b_0)\) is the center of the artificial frame and \(f\) is the focal length of the camera. By using a perspective transformation we can define:

\[
\frac{f}{Z} = a = a_0 + \frac{fX}{Z} \\
\frac{b}{Z} = b = b_0 + \frac{fY}{Z}
\]

Using homogeneous coordinates, can be performed \(Q\) in a matrix.

\[
\begin{bmatrix}
A \\
B \\
C
\end{bmatrix} = \begin{bmatrix}
\frac{1}{p_x} & 0 & a_0 \\
0 & \frac{1}{p_y} & b_0 \\
0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
f & 0 & 0 & 0 \\
0 & f & 0 & 0 \\
0 & 0 & 1 & 1
\end{bmatrix} \begin{bmatrix}
X_Q \\
Y_Q \\
Z_Q \\
1
\end{bmatrix}
\]

(15)

where \(a = \frac{1}{p_x}\) and \(b = \frac{1}{p_y}\)

If we define that \(f_x = \frac{f}{p_x}\) and \(f_y = \frac{f}{p_y}\) are the focal lengths in \(x\) and \(y\) axis respectively, finally a matrix can be arranged as

\[
U = \begin{bmatrix}
f_x & 0 & 0 & 0 \\
f_y & 0 & 0 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\]

(16)

Where \(U\) is an intrinsic matrix of camera. The projection of point \(Q\) onto the camera screen is

\[
q = U \cdot Q
\]

(17)

Both cameras have to find the intrinsic matrix in the same way. By this, Bouquet and Jean-Yves (2008) created a MATLAB toolbox, which can be used to find out all of the parameters. This method requires, that the camera observes a chessboard pattern at different orientations. After the intrinsic parameters are estimated, the next step is to calculate the transformation between the two cameras. Assume, the object are projected onto the CCD frame and PMD frame with different orientations, the CCD frame is transformed into the PMD frame through a rotation and translation matrix. Denote \((x_{PMD}, y_{PMD}, z_{PMD})\) are the coordinate of PMD camera on artifical frame and \((x_{CCD}, y_{CCD}, z_{CCD})\) are the coordinates of the CCD camera frame, the CCD frame can project onto PMD frame using equation (18).

\[
\begin{bmatrix}
x_{PMD} \\
y_{PMD} \\
z_{PMD}
\end{bmatrix} = [R, t] \begin{bmatrix}
x_{CCD} \\
y_{CCD} \\
z_{CCD}
\end{bmatrix} + \begin{bmatrix}
0 \\
0 \\
1
\end{bmatrix}
\]

(18)

\[
q_{PMD} = [R, t] q_{CCD}
\]

(19)

We have to find the intrinsic matrix for both cameras in the same way. After the intrinsic parameters are estimated, the next step is to calculate the transformation between the two cameras.

The relative vector can be generated from the calibration model. Table 1 shows the \(R\) and \(T\) which the two cameras relate to each other. We can see the CCD camera is far away from the PMD center, approximate 14.31, 63.96 and 70.83 mm in the \(x\), \(y\) and \(z\) axis respectively. The Rotation from the PMD center is 0.05058, 0.07940 and -0.01120 degrees of roll, pitch and yaw angle respectively. Fig. 12 shows the output of CCD and PMD camera before and after the combination approach. The figure expresses the difference between the field of view of both cameras. The precise camera calibration model of the previous section is essential to minimize the error, which may occur from the combined hardware setup. Fig. 12 (a) shows the image output from the field of view from 2D camera. Fig. 12 (b) shows the depth data from PMD camera in gray scale mode. Fig. 12 (c) shows the output after combination 2D and PMD camera. The experiment proves that the calibration model can register the contour to the depth data and generates an output, which looks more reliable. The output of the combination is the base image frame for using a PMD camera to detect the object in 3D environments and to build a 3D map.

![Fig. 12. The output before/after combination (a) 2D image (b) PMD data (c) combination 2D/PMD](image)

**Table 1. Relative coordinate CCD/PMD**

<table>
<thead>
<tr>
<th>Rotation vector(R)</th>
<th>Translation vector(T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0.05058 0.07940 −0.01120]</td>
<td>[14.31872 63.96501 70.83500]</td>
</tr>
</tbody>
</table>

The output from the field of view from both 2D and PMD cameras are registered. It can be assumed that each pixel of CCD data are registered, the coordinates of both pixels are related to each other. We can see the CCD camera is far away from the PMD center, approximate 14.31, 63.96 and 70.83 mm in the \(x\), \(y\) and \(z\) axis respectively. The Rotation from the PMD center is 0.05058, 0.07940 and -0.01120 degrees of roll, pitch and yaw angle respectively. Fig. 12 shows the output of CCD and PMD camera before and after the combination approach. The figure expresses the difference between the field of view of both cameras. The precise camera calibration model of the previous section is essential to minimize the error, which may occur from the combined hardware setup. Fig. 12 (a) shows the image output from the field of view from 2D camera. Fig. 12 (b) shows the depth data from PMD camera in gray scale mode. Fig. 12 (c) shows the output after combination 2D and PMD camera. The experiment proves that the calibration model can register the contour to the depth data and generates an output, which looks more reliable. The output of the combination is the base image frame for using a PMD camera to detect the object in 3D environments and to build a 3D map.

**Fig. 13. 3D artificial landmark detection**

4.2 Object Detection in A 3D Environment

In an experiment the advantages using a combination between the 3D PMD camera and a normal CCD camera should be tested. As the object which is obtained to be detected the artificial landmark is used. After 2D and 3D data are registered, the coordinates of both pixels are registered. It can be assumed that each pixel of CCD and PMD camera are the same. The object detection technique which can be acquired from the CCD camera is transferred to the 3D coordinate system. A proper distance calibration is absolutely necessary due to the algorithm. It is dependent on an accurate geometric reconstruction.
Fig. 13 shows the acquisition of an artificial landmark detection. The artificial landmark was detected in a 3D environment. It can be applied for the mobile robot applications e.g. mobile robot can search the interested objects in the unknown environment.

5. 3D MAP GENERATION

This section shows the real time operation of a 3D mapping. The experiment was tested for generating the three dimensional mapping from data of a combination between 2D and 3D cameras. During the recording of the 3D map, the robot moves autonomously or teleoperatively along a corridor on a specified path. Because of the limited aperture angle of the PMD camera with less than 40 degrees, the camera is mounted at the side of the robot. In this way the camera observes the area on the left hand of the robot and it can be guaranteed that the wall is inside of the PMD image at any time, while the robot is driving through the corridor.

The matching algorithms for generating a 3D map out of the sequently recorded PMD images based on the ICP algorithm[Paul J. Besl (1992)]. To accelerate the processing time an initial transformation based on the described self localization algorithm will be executed before running the ICP algorithm. This yields to a more precise calculation of the image matching procedure, accordingly.

Fig. 14. 3D mapping zoom in a short distance

Fig. 15. 3D mapping at the indoor corridor

The combination of the cameras results in an output that can describe the contour and show more understanding detail of 3D environment to the users, instead use only PMD camera. Fig. 14 zooms in the short distance in the map along the corner around 10 meters. We can see the contour of the corner and details of that scenario. The coloured map avoids a good view to the user for the complex environment and create the three dimension environment. With the colour informations inside of the map, it is easy for a user to interpret the map. One prominent problem to use a PMD camera to build a 3D mapping, is the small field of view. All results could express only one side (right or left hand side) because of this the camera must turn on one side, otherwise it couldn’t generate any surrounding area because of the low field of view. Methods of resolution of the described problem is to build the rotating mechanical part which can rotate from 0-180 degree can probably improve the quality of 3D mapping. Another possibility is to use more than one camera, one in front and one camera at each side of the robot.

6. CONCLUSION

In the previous sections the integration of the PMD camera for mobile robot self localization and the 3D map building with a sensor combination of 3D PMD and normal CCD sensor were described. It can be verified, that the combination of normal wheel encoder and image vectors, which were calculated from the PMD images, provides a good possibility to determine the relative position of a mobile robot. The relative self localization fused with the absolute self localization, using the detection of artificial landmarks, offers an excellent basis for 3D map building. The combination of 2D/3D camera can enhance the performance of PMD camera. That can apply to use for object detection in the complex environment and create the three dimension environment. With the colour informations inside of the map, it is easy for a user to interpret the map. One prominent problem to use a PMD camera to build a 3D mapping, is the small field of view. All results could express only one side (right or left hand side) because of this the camera must turn on one side, otherwise it couldn’t generate any surrounding area because of the low field of view. Methods of resolution of the described problem is to build the rotating mechanical part which can rotate from 0-180 degree can probably improve the quality of 3D mapping. Another possibility is to use more than one camera, one in front and one camera at each side of the robot.

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