Monoscopic 6DOF Detection using a Laser Pointer

Elmar Bomberg, Marc Erich Latoschik

PO 100 131
Bielefeld University
33501 Bielefeld
Tel.: +49 (0)521 106 2923
Fax: +49 (0)521 106 2962
E-Mail: {ebomberg—marcl}@techfak.uni-bielefeld.de

Abstract: This article illustrates the detection of 6 degrees of freedom (DOF) by utilizing a simple laser pointer device and a camera. The laser pointer device is augmented by a diffraction grating to project a unique laser grid onto the projection planes used in projection based immersive VR-setups. The distortion of the projected grid is then used to calculate the additional degrees of freedom as required for human-computer interaction purposes.

Keywords: laser pointer, 6DOF detection, interaction

1 Introduction and Related Work

Interaction in Virtual Environments requires information about position and orientation of specific interaction tools or body parts of users. This information is commonly provided by various tracking devices based on, e.g., mechanical, electromagnetic, ultra-sonic, inertial, gyroscopic, or optical principles. Besides qualitative aspects of resolution, data-rate and accuracy, these devices in general differ in their hardware setup which includes the control behavior (active or passive) and the use of active or passive markers or sensors. For example, several successful optical tracking systems nowadays use reflective IR-markers lit by IR-LEDs which are registered by IR-cameras to track uniquely arranged sensor targets. An alternative approach uses active sensors which emit light and save the additional need of a lighting device but require additional power sources, mounts and/or cabling.

Here, laser pointers present a lightweight and low-cost solution for simple interaction purposes where full body captures are not required and simple tool based operations like select and drag-and-drop are sufficient. Unfortunately, common laser pointers only provide 2DOF, i.e., when their emitted laser beam intersects a plane that generates a laser point recognizable by a camera. In this article, we illustrate a modified laser pointer which is capable of providing 6DOF while preserving all favorable properties.

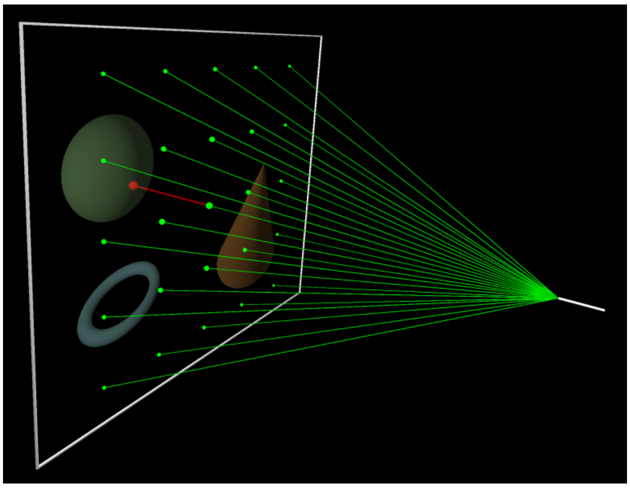

Figure 1: Scheme of the direct interaction with the laser-pointer device augemented by a cross diffraction grating

Several approaches use custom-built laser devices which project more then one laser spot on one or more projection screens to provide additional DOF. Matveyev [MG03] proposes a multiple-point technique with a infrared laser-based interaction device. It projects three infrared laser spots on a projection screen using one base-, and two auxiliary laser-beams. The first auxiliary beam has a fixed angle of divergence, whereas the other can change its deviation angle mechanically relative to the base beam. With this technique the interaction device has 5DOF, two for movement in the x- and y- direction, one for rotation in the x,y-plane, one for the shift along z-axis and one for mouse emulation purposes.

The *Hedgehog*, proposed by Vorozcovs et. al [VHS05], provides 6DOF in a fully-enclosed VR display. The device consists of 17 laser diodes with 645nm wavelength in a symmetrical hemispherical arrangement, where each laser diode is placed in a 45 degree angle from each other and is individually controlled by a PIC microcontroller through a serial interface. The fully-enclosed VR display has at least one camera for each projection screen to track the laser spot positions produced by the Hedgehog. The proposed technique allows to determine the 6DOF with a angular resolution of 0.01 degrees RMS and position resolution of 0.2 mm RMS.

1.1 Discussion

Matveyev and Göbels [MG03] approach has the disadvantage, that the additional DOF instantly decrease when the number of the only three available laser spots on the projection screen drops. Furthermore, the laser spot distance required for depth calculation has to be very small to allow a high interaction radius, which requires a high camera resolution and precise subpixel estimation.

Vorozcovs et. al [VHS05] proposed technique allows to determine 6DOF in a high accuracy and reasonable update rate but ideally requires multiple projection screens and a considerable complex hardware installation.

The laser pointer based tracking system in this work, illustrated in Figure 1, proposes a technique to determine 6DOF relative to a single projection based immersive VR-setup and overcomes some of the limitations found in [MG03]. In addition, the hardware costs for the laser pointer based interaction device and the digital camera are very low in comparison with other optical tracking systems.

2 Concept

2.1 Augmented Device

The augmented device consists primarily of three components: A customary green laser pointer, a cross diffraction grating and a custom-built mount. The custom-built mount allows to attach and adjust the cross diffraction grating orthogonal to the laser pointer. An overview of the custom-built mount is illustrated in Figure 2. In combination the components project a regular laser point grid onto a planar screen, if the device is oriented perpendicular.

The choice of the laser output power and the cross diffraction grating depends on the condition, that either the whole or a part of the projected grid should utilize the entire projection area with a maximum number of projected laser points. In this case the complete resolution of the camera can be used to determine the 6DOF. Nevertheless the output power of the laser pointer still has to fulfill laser safety regulations. The physical parameters of the device, like laser output power and the wavelength determine the characteristics of the projected grid, where the intensity of the center order to higher orders decreases gaussian-shaped. The laser pointer wavelength determines the angle of divergence between the laser beams as well as the size of the projected laser point grid on the projection screen.

In our augmented device we are using a commercial holographic cross diffraction grating, which usually finds application in entertainment, i.e., in laser shows. This grating has a groove period of approximately 6055.77 nm and a groove density of 165.1 grooves per millimeter. In combination with a laser pointer of 532 nm wavelength, the angle of divergence between the laser beams of zero and first order is approximately 5.03 degrees. This green laser pointer has been chosen, because their exists a tight dependency between the emitting device (the laser device) and the sensity device (the camera), in our case a 1CCD-Chip bayer camera, which is more sensitive for the green color, as it contains two times more green than red and blue pixels. In view of laser safety reasons the output power of the laser pointer is lower than 1 mw. It is possible to use a laser pointer with an output power up to 4 mw, because the cross diffraction grating diminishes the output power in the zero order to a quarter of its former value.

To mount the cross diffraction grating on the laser pointer a special mount has been developed. Figure 2 shows the assembly of the grating mount.

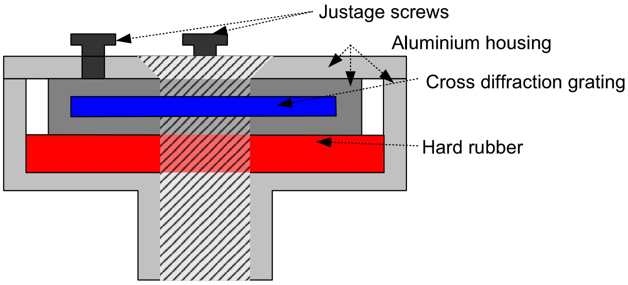

Figure 2: Grating Mount

It consists of a separate aluminum housing with apertures for the laser beam, to capsule the diffraction grating. This aluminum housing lies on a hard rubber layer and allows to adjust the capsulated diffraction grating at two axes. The center cross of the projected grid may not be bent and can be calibrated in comparison with an orthogonal line cross on a sheet of paper.

2.2 Camera Installation

In order to detect the projected laser points, we are using a 1CCD-Chip digital firewire camera with a resolution of 640x480 and a framerate of 30 fps. The camera provides non-interpolated color images, and thus allow a more precise image processing. Figure 3 shows the camera setup in case of a rear projection screen. The camera is mounted below the video projector, and observes the projection screen via the projection mirror. This place provides an ideal image of the projection screen with a minimum of perspective distortion possible (see [OS02]).

An in front of the screen camera installation is possible, but has the disadvantage of a more complex image processing and can furthermore lead to occlusions between the camera and the projection screen.

2.3 Image Processing and Calibration

The laser point detection in our implementation is based on a simple threshold operation to identify bright pixels in the color of the laser pointer wavelength. The subpixel-precise position is calculated by an intensity weighted sum of the pixels belonging to one laser spot as described in [OS02]. In higher orders of the laser point grid the subpixel-precision decreases, because in that case the laser spot size corresponds to only one pixel of the camera image. For the calculation of the real 2D laser point position in projection screen coordinates, the radial and the perspective distortion

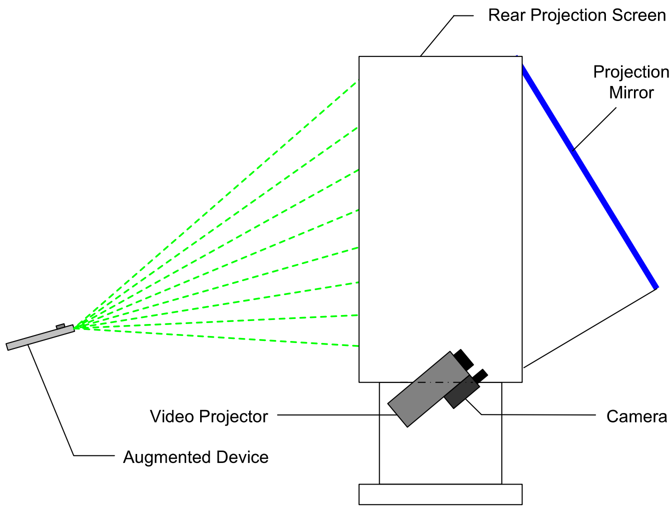

Figure 3: Setup of the laser-pointer based tracking system.

have to be measured beforehand. The radial distortion parameters are determined by using a planar chessboard pattern. To calculate the perspective transformation, a projective planar transformation named homography is computed [HZ03] that transforms the 2D undistorted (radial) camera image coordinates into projections screen coordinates. For this purpose four measured undistorted point coordinates in the camera image and their corresponding projection screen coordinates are determined. These four points are determined by projecting a standard laser pointer into the four corners of the projection screen and their subpixel-precise laser point detection according to [VHS05]. Afterwards these coordinates are transformed in radial undistorted coordinates. The corresponding projection screen coordinates are measured manually. We have chosen the upper left corner of the projection screen as point of origin of the projection screen coordinate system.

2.4 Laser Point Grid Calculation

For the determination four basic calculation steps are neccessary:

1. The physical calculation of the projected grid laser point coordinates, when the augmented device is oriented orthogonal to the projection screen.

2. The grid mapping, that assigns the detected laser point positions to a 2D order (m,n) of the grid model (see Section 2.5) .

3. The laser beam triangle calculation (see Section 2.6).

4. The 6DOF Computation (see Section 2.7).

For this calculation of the projected grid laser point coordinates, the laser pointer wavelength λ, the diffraction grating groove period b, the distance to the projection screen l and the 2D order positions (m,n), where $m,n \in \mathbb{Z}$, are needed. In general the order positions in physics have positive values. For the calculation of the laser point grid, order position values have been extended to negative values, and represent the grid model in this work. This allows to calculate unique positions for each order, where the zero order marks the center of origin in the laser point grid coordinate system.

The physical order position (x,y), where $x,y \in \mathbb{R}$, can be calculated by the following formulas, in which r denotes the distance between the $(0,0)$-order and the arbitrary order (m,n):

$$r = \frac{l}{b} \frac{\sqrt{n^2+m^2}\lambda}{\sqrt{1-(\frac{\sqrt{n^2+m^2}\lambda}{b})^2}} \tag{1}$$

$$x = r\frac{n}{|n|}\frac{1}{\sqrt{1+(\frac{m}{n})^2}} \tag{2}$$

$$y = r\frac{n}{|n|}\frac{(\frac{m}{n})}{\sqrt{1+(\frac{m}{n})^2}} \tag{3}$$

If $n = 0$ then:

$$x = 0 \tag{4}$$

$$y = \frac{m}{|m|}r \tag{5}$$

Figure 4 shows one example for the calculation of the projected laser point grid for the augmented device parameters (wavelength,groove period, distance) . This illustrates that the projected laser points of adjacent orders in horizontal and vertical direction are not equidistant.

The grid positions are the bases for calculating the angles of divergence between two orders, which in turn is required for the 6DOF determination.

2.5 Grid Mapping Heuristic

In the following, a grid mapping, that assigns the detected laser point positions to a 2D order (m,n) of the grid model, has to be performed. This grid assignment is not unique because of the laser point grids rotational symmetry in the projection plane. Consequently the mapping of the grid model changes with every quarter turn. For the whole grid assignment, the following steps are processed:

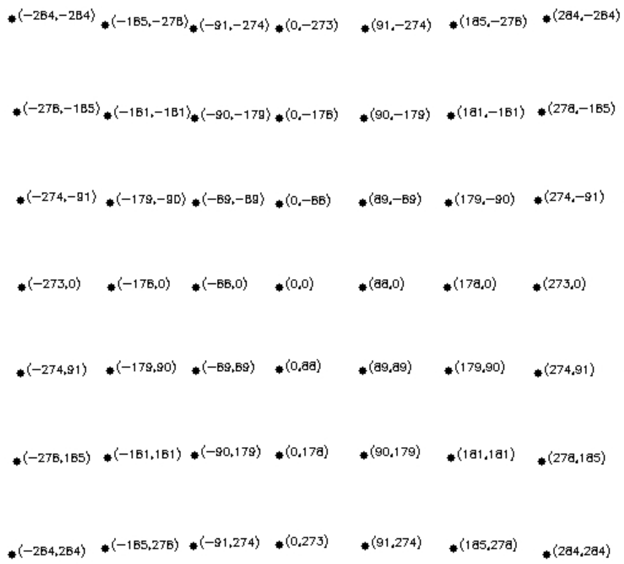

Figure 4: Calculation of the laser point positions for a 2D cross diffraction grating. $\lambda = 532nm$, $b = 6055.77nm$, $l = 1000m$, Order $(-3,-3)$ to $(3,3)$

1. Assignment of the zero order (0,0) to the grid model, which can be identified through the laser point pixel size.

2. Determination and validation of the 3x3 neighborhood surrounding the zero order (0,0) and assignment to the grid model.

3. If the first 3x3 neighborhood is not complete or correct, the determination and validation of their 3x3 neighborhood is processed on the previously found neighbors surrounding the zero order, until a valid neighborhood has been found.

4. Mapping of the orders based on the first assigned orders using the laser beam triangle calculation (see section 2.6).

To find the 3x3 neighborhood of the examined order, the search method illustrated in Figure 5 is applied using following notation: *NC* is the center of the neighborhood, *NN* are the nearest neighbors, *ON* are the opposite neighbors, *FoundLaserPointsList* is the list of all detected laser points and *FoundNeighborsList* denotes the found neighbors. In the first step of the neighborhood search the examined order, in this case the center of the neighborhood *NC* is deleted from the *FoundLaserPointsList*. Afterwards following steps are applied four times:

1. Find the nearest laser point *NN* next to the examined order *NC* in the *FoundLaserPointList*.

2. Find the nearest laser point *ON* opposite to the previously found laser point *NN* relative to the examined order *NC* and add *NN* and *ON* to the *FoundNeighborsList*.

3. Delete all laser points from the *FoundLaserPointsList*, which approximately lie on the straight line with the two previously found laser points *NN* and *ON*.

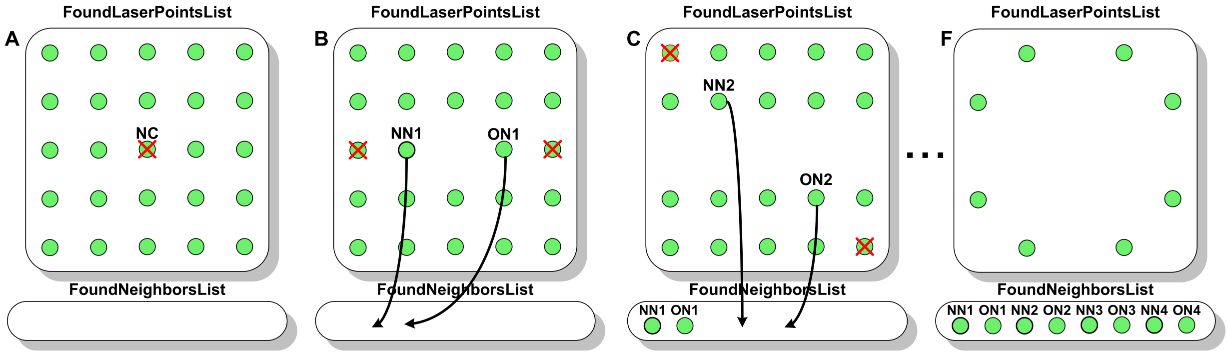

Figure 5: Scheme for 3x3 neighborhood search method

The found laser points in the *FoundNeighborsList* are validated afterwards, whether they belong to a 4-sided polygon surrounding the examined order. So the valid 3x3 neighborhood is assigned to the grid model. This first mapping builds the base for the assignment of the remaining found grid laser points and allows to predict the grid laser point positions by using the laser beam triangle calculation in section 2.6. These predicted positions are compared with the matching grid laser points and assigned to the grid model if they are approximately equal.

2.6 Laser beam triangle calculation

The grid laser points assigned to the grid model, provide additional information needed to calculate the angles of divergence between two arbitrary orders. Besides at least five laser point positions of the grid model are necessary to calculate the 6DOF. These five points have to lie on two straight lines, whereas each is described by three laser point positions. These straight lines have to intersect in one point as shown in Figure 8. Each straight line in conjunction with the position of the augmented device (AD) composes a triangle and will be denoted as laser beam triangle. Figure 6 shows such a laser beam triangle with the laser points P_1,P_2,P_3, the augmented device *LD*, the laser beam distances b_1,c,b_2, the laser point distances a_1,a_2 and the angles of divergence α_1, α_2.

All parameters of the laser beam triangle, can be calculated by the distances a_1 and a_2, and the known angles α_1 and α_2. Some trigonometric relationships lead to following equation:

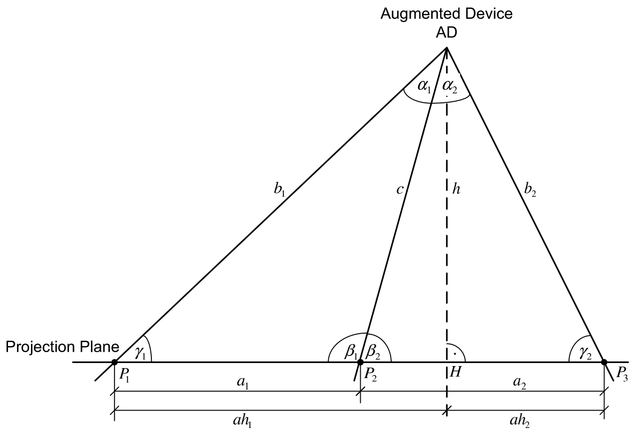

Figure 6: Scheme of the laser beam triangle calculation

$$\frac{a_1}{a_2} = \frac{b_1}{b_2} \frac{\sin(\alpha_1)}{\sin(\alpha_2)} \tag{6}$$

After the application of the law of cosine we get:

$$(a_1 + a_2)^2 = b_1^2 + b_2^2 - 2b_1 b_2 \cos(\alpha_1 + \alpha_2) \tag{7}$$

Equation 6 solved to b_2 and substituted in equation 7:

$$(a_1 + a_2)^2 = b_1^2 + \left(\frac{a_2 b_1}{a_1} \frac{\sin(\alpha_1)}{\sin(\alpha_2)} \right)^2 - 2b_1 \left(\frac{a_2 b_1}{a_1} \frac{\sin(\alpha_1)}{\sin(\alpha_2)} \right) \cos(\alpha_1 + \alpha_2) \tag{8}$$

Solving the quadratic equation with the assumption that $a_1, a_2 \in \mathbb{R}^+$ and $\alpha_1, \alpha_2 \in [0, 90]$

$$b_1 = \frac{a_1 (a_1 + a_2)}{\sqrt{a_1^2 - 2\cos(\alpha_1 + \alpha_2) a_1 a_2 \frac{\sin(\alpha_1)}{\sin(\alpha_2)} + a_2^2 \left(\frac{\sin(\alpha_1)}{\sin(\alpha_2)} \right)^2}} \tag{9}$$

In a similar way the distance b_2 can be calculated. The other parameters of the laser beam triangle $\gamma_1, \gamma_2, \beta_1, \beta_2, c, h, ah_1, ah_2$ can be computed by simple trigonometric relationships.

2.7 6DOF Calculation

The computation of the 3D position and orientation of the augmented device is illustrated in Figure 7 and 8. In this figures the five projection laser points are denoted as $A(a_x|a_y|0)$, $B(b_x|b_y|0)$, $C(c_x|c_y|0)$, $D(d_x|d_y|0)$, $E(e_x|e_y|0)$.

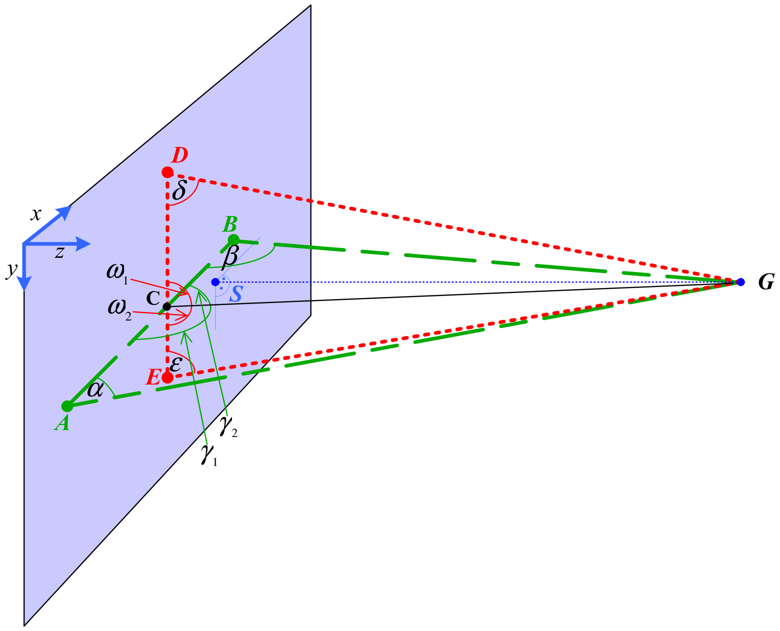

Figure 7: 3D-scheme for 6DOF Calculation of the augmented device

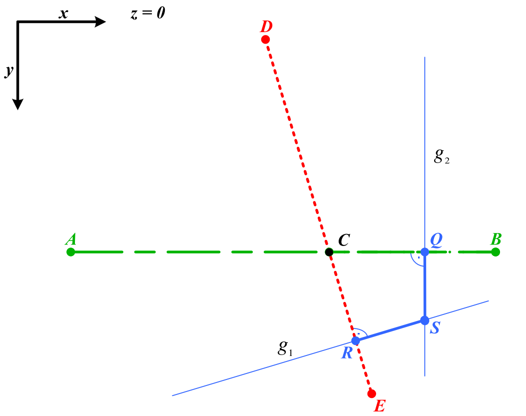

Figure 8: 2D-scheme for 6DOF Calculation of the augmented device

The points $Q(q_x|q_y|0)$, $R(r_x|r_y|0)$ denote the perpendicular bases from the augmented device position $G(g_x|g_y|g_z)$ to the straight lines $\overline{AB}$ and $\overline{DE}$. With the five laser points positions the distances $|\overrightarrow{AC}|$, $|\overrightarrow{CB}|$ and $|\overrightarrow{DC}|$, $|\overrightarrow{CE}|$ can be determined. The angles of divergence $\sphericalangle(DGC)$, $\sphericalangle(CGE)$, $\sphericalangle(AGC)$, $\sphericalangle(CGB)$ can be computed from the known 2D-orders (m,n) belonging to the laser points. This informations allow to compute the laser beam triangles (AGB) and (DGE). To get the perpendicular base $S(s_x|s_y|0)$ from G to the projection plane, the intersection of following linear equations is computed:

$$g_1 : \overrightarrow{x} = \left(\overrightarrow{0Q} + \lambda_1 \overrightarrow{n_{AB}}\right) \tag{10}$$

$$g_2 : \overrightarrow{x} = \left(\overrightarrow{0R} + \lambda_2 \overrightarrow{n_{DE}}\right) \tag{11}$$

with the normal vectors $\overrightarrow{n_{AB}} = \begin{pmatrix} -AB_y \\ AB_x \\ 0 \end{pmatrix}$ and $\overrightarrow{n_{DE}} = \begin{pmatrix} -DE_y \\ DE_x \\ 0 \end{pmatrix}$

So the intersection point S can be computed:

$$S = \begin{pmatrix} q_x + n_{AB_x} \frac{q_y n_{DE_x} - r_y n_{DE_x} - q_x n_{DE_y} + r_x n_{DE_y}}{n_{AB_x} n_{DE_y} - n_{DE_x} n_{AB_y}} \\ q_y + n_{AB_y} \frac{q_y n_{DE_x} - r_y n_{DE_x} - q_x n_{DE_y} + r_x n_{DE_y}}{n_{AB_x} n_{DE_y} - n_{DE_x} n_{AB_y}} \\ 0 \end{pmatrix} \tag{12}$$

The x and y coordinates of the augmented device are given by s_x and s_y, where the z coordinate is given by the length $|\overrightarrow{SG}|$:

$$|\overrightarrow{SG}| = \sqrt{|\overrightarrow{AG}|^2 - |\overrightarrow{SA}|^2} \tag{13}$$

The 3D position of the augmented device G is:

$$\overrightarrow{0G} = \overrightarrow{0S} + \overrightarrow{SG} = \begin{pmatrix} s_x \\ s_y \\ |SG| \end{pmatrix} \tag{14}$$

The direction vector of the pointing beam $\overrightarrow{GC}$ is given by:

$$\overrightarrow{GC} = \overrightarrow{0G} - \overrightarrow{0C} \tag{15}$$

With $\overrightarrow{0G}$ and $\overrightarrow{GC}$ the determination of five DOF are unique done. The last DOF is approximated by the rotation angle between the straight line of the (m,0)-orders and the x-axes. This allows to determine a rotation angle between 0 and 90 degree, because of the rotation symmetry. Higher rotation angles can be computed by continuous tracking of the laser point grid rotation.

2.8 Conclusion

We have presented an inexpensive new active optical tracking technique, which allows to determine 6DOF relative to single projection screen. The devices' 6DOF (five absolute and one relative) provide interaction with a virtual environment in a intuitive direct manner.

First tests reveal that the accuracy of the 6DOF determination decreases stepwise with the number of detected laser points belonging to one laser beam triangle. To improve the accuracy, a grayscale firewire camera with a higher resolution would enhance the subpixel-precise laser point detection. Furthermore, a laser pointer with a higher laser output power, and a diffraction grating with a smaller groove period to increase the angle of divergence between the orders would improve the laser point detection.

The use of multiple devices can be obtained by using more than one grayscale camera with wavelength bandpass filters and laser pointers with different wavelengths. Another alternative is a time-division multiplexing technique proposed by Pavlovych and Stuerzlinger [PS04]. In future work, a Kalman filter [Kal60] for the laser point detection and the 6DOF determination, will be implemented to eliminate the hand tremor and to smooth the 6DOF position computation.

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