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Integrating a Short Range Laser Probe with a 6-DOF Vertical Robot Arm and a Rotary Table (RAAD 2008)

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Abstract. This article presents a 3D laser scanning system which consists of a short range laser probe mounted on a 6-DOF vertical robot arm, and a rotary table which holds the scanned workpiece. The steps required to be carried so that all the components work together, and the transformations needed for aligning the laser probe measurements into a single coordinate system by reading the instantaneous position from the robot arm and rotary table, including calibration issues, are discussed here.

Keywords. 3D Laser Scanning, Synchronization, Calibration, Robot Motion Control.

1. Introduction

This work is part of a project whose goal is to develop a 3D laser scanner system by using a 6-DOF vertical articulated robot arm to move a triangulation-based laser probe around the work piece, which is placed on a rotary table. The manipulator has a spherical working envelope with a radius of 650 mm, and the laser probe is able to measure distances from 100 to 200 millimetres with 25 μm accuracy. The rotary table encoder has a resolution of 0.03 degrees. An overview of the scanning system's hardware and software is represented respectively in Figs. 1 and 2.

The robot arm will move the laser probe around the work piece being scanned by using either predefined or adaptive scanning paths, which are computed in real-time while the scanner is discovering the work piece features. The work piece is placed on the rotary table, which rotates smoothly and moves synchronously with the robot arm. The system will be used for reproducing of existing workpieces on a 4-axis CNC milling machine.

The laser probe uses a linear laser module, which projects a red light line on the scanned workpiece. The line is detected by the two cameras located on the laser probe, and the work piece contour along the laser line is extracted as a set of points in Cartesian coordinates using the triangulation method (Nguyen, 1995). The robot arm and rotary table form a 7-DOF kinematic chain that can move the laser probe to a precise location with respect to the work piece, according to the scanning trajectory. The measured points lie in the laser plane, which is the plane determined by the laser rays. Since the position of the laser probe, and therefore the laser plane, is known relative to the work piece every time a measurement is taken, the measured points can be transformed into a unique reference frame, which is attached to the work piece. The points measured and aligned form a point cloud model of the 3D shape of the workpiece.

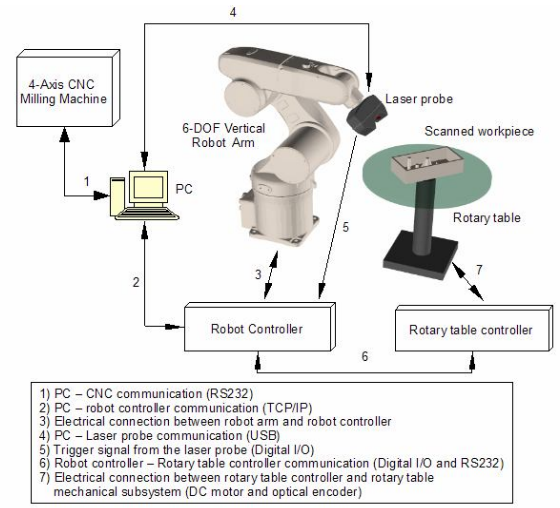

Fig. 1. Hardware diagram of the laser scanning system

The motion of the rotary table is computed by the *Rotary table planner* (Fig. 2), which rotates the table in order to make sure that the robot arm will be always in range in order to position the laser probe at the location requested by the trajectory generator.

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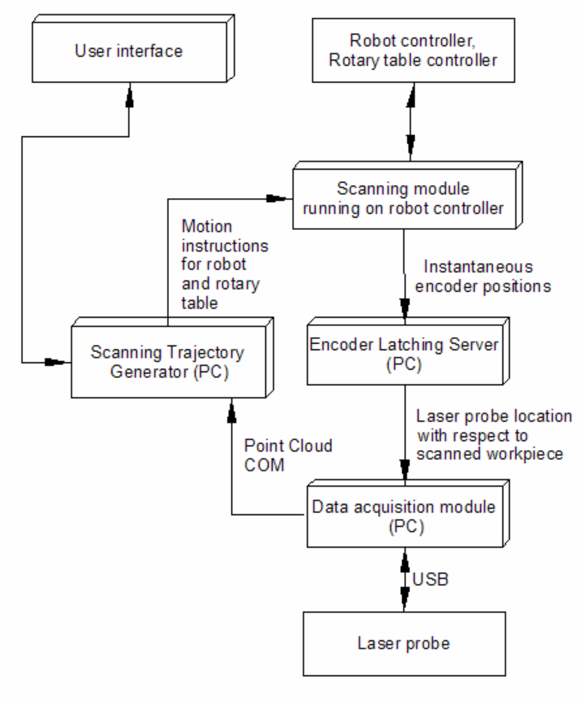


Fig. 2. Software diagram of the laser scanning system

2. Communication and synchronization

The laser probe is connected to the PC using the USB interface. The *Data acquisition module* takes measurements for the laser probe, as a set of 2D points in the laser plane. In order to be able to align the points into the workpiece's reference frame, this module has to know the instantaneous pose (i.e. position and orientation) of the laser probe with respect to the workpiece. The pose is computed by the *Encoder latching server* module, which reads the encoder readings from the robot arm and rotary table controllers from a TCP/IP connection. Using the kinematic model of the system, which will be presented in Section 3, this module is able to compute the instantaneous location of the laser probe from encoder data, and send it to the data acquisition module, in *X-Y-Z-Yaw-Pitch-Roll* format.

The robot arm and rotary table controllers have the ability to latch their instantaneous position using an external trigger signal, which is sent by the laser probe every time a measurement is made. This digital signal is connected to a fast digital input, both on the robot controller and the rotary table controller. The scanning rate is between 50 and 150 frames/second, each frame containing a set of 2D points. The two controllers are able to detect digital inputs and latch their position within less than 1 millisecond.

The *scanning trajectory generator* is able to compute either predefined or adaptive scanning paths, based on the type and approximate dimensions of the scanned workpiece. The workpieces may be small molds, free-form surfaces like art objects, electronic parts and small-scale models of real objects.

3. Aligning the measurements

The kinematic model of the scanning system will be presented here, with the transformations required to align the measurements into the work piece reference frame.

3.1. Reference frame assignments

The 7-DOF kinematic chain is modelled using the Denavit-Hartenberg convention, as shown in Fig. 3. One may imagine the rotary table fixed and the robotic arm rotating around the work piece, considering that the effect of the 7th degree of freedom is applied before the other 6 links of the arm. The location of the rotary table relative to robot arm is modelled as a link 0, or link R (see Tab. 1).

The measurements from the laser probe are taken in its local reference frame, which is $X_L Y_L Z_L$. Since the laser plane is the $Y_L Z_L$ plane, the X component of every measurement will be 0, and the other two components are determined using the triangulation method, described in (Borangiu et al., 2008).

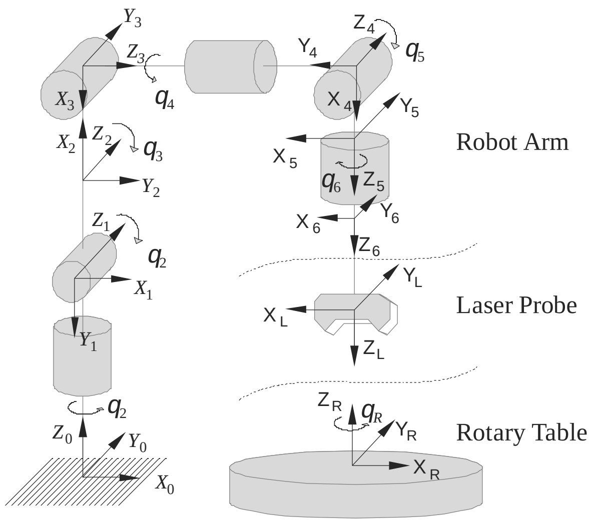


Fig. 3. Denavit-Hartenberg reference frame assignment

Tab. 1. Denavit-Hartenberg parameters

Link	a_i [mm]	d_i [mm]	α_i [deg]	θ_i [deg]
R / 0	–500	–200	0	$-\theta_R$
1	75	335	–90	θ_1
2	270	0	0	θ_2
3	–90	0	90	θ_3
4	0	295	–90	θ_4
5	0	0	90	θ_5
6	0	80	0	θ_6

The transformation from $X_0 Y_0 Z_0$ to $X_6 Y_6 Z_6$ is the direct kinematics of the 6-DOF arm and, according to Denavit-Hartenberg convention (Spong, 2005), it is obtained by composing the individual homogeneous transforms for every link:

$$T_i^{i-1} = R_Z(\theta_i) \cdot T(a_i, 0, d_i) \cdot R_X(\alpha_i), \quad i = \overline{1,6} \qquad (1)$$

$$T_0^6(\theta_{1..6}) = \prod_{i=1}^{6} T_i^{i-1} \qquad (2)$$

The transformation from the 6th link of the robot to the laser probe reference frame is T_L^6 (Fig. 4). The ideal expression of this transformation, given in Eq. (3), is based on the dimensions of the fixture, which creates a rigid assembly between the robot flange and the laser probe (Sciavicco, 1996).

$$T_L^6 = R_Z(90°) \cdot T(0, -100, 0) \qquad (3)$$

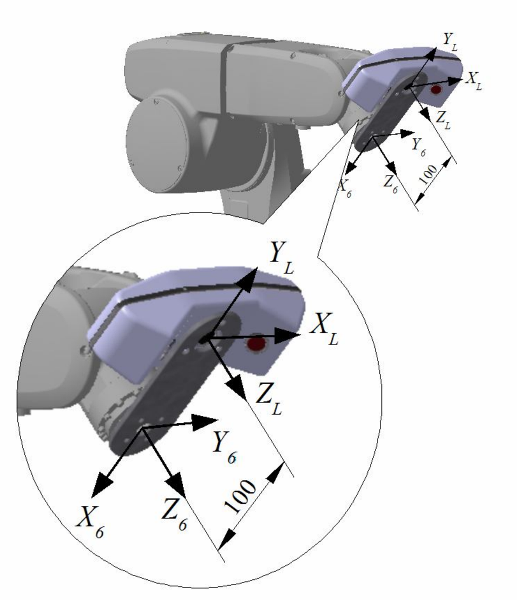


Fig. 4. Robot – Laser Probe transformation

When performing the *robot – laser probe calibration*, the exact expression of this transformation, which compensates the mechanical errors, will be computed. The transformation obtained after calibration may contain a rotation around an arbitrary axis and offsets along *X*, *Y* and *Z*.

The transformation from the rotary table to the robot base is T_0^R, and its ideal expression is, according to Tab. 1:

$$T_0^R(\theta_R) = T(500, 0, 200) \cdot R_Z(\theta_R) \qquad (4)$$

Since the position of the rotary table with respect to the robot base is not exactly the designed one, the transformation from Eq. (4) has to be determined by performing the *robot – rotary table calibration.*

3.2. Alignment equation

In order to align the measurements from the laser probe, which are in the $X_L Y_L Z_L$ reference frame, to the work piece reference frame (which is the same as the rotary table reference frame $X_R Y_R Z_R$), the data acquisition software module has to pre multiply all the measurements with the alignment transformation:

$$T_{align} = T_L^R = T_0^R(\theta_R) \cdot T_6^0(\theta_{1...6}) \cdot T_6^L \qquad (5)$$

This transformation is computed by the encoder latching server module, which, after converting it to the *X-Y-Z-Yaw-Pitch-Roll* format, sends it to the data acquisition module which performs the alignment of the scanned points, to obtain the point cloud representing the scanned workpiece.

4. Calibration issues

As shown in the previous section, there are two transformation matrices that are only known with approximation. These are the transformation between the 6th link of the robot and the laser probe T_L^6, which will be established by *robot – laser probe calibration*, and the transformation between the rotary table and robot base, $T_0^R(\theta_R)$, determined by *robot – rotary table calibration*. Their ideal expression is determined by the dimensions of the mechanical fixtures that link these elements together.

However, small errors in execution and assembly of the fixtures may introduce large errors in the measurements. Therefore, instead of manufacturing fixtures with very tight tolerances, the preferred solution was to attempt to compensate the errors in software, using calibration (Goldberg, 1994).

The data acquisition module which accompanies the laser probe used in this project provides a routine for performing the *robot – laser probe calibration*, which involves placing an object at known locations and moving the laser probe until it is able to locate the object. By comparing the known object locations with the locations identified by the laser probe, the calibration routine provides a method for computing T_L^6, and therefore this article will focus on determining the second transformation, $T_0^R(\theta_R)$. A method for checking whether the two calibration procedures succeed will be presented.

4.1. Types of misalignment

The reference frame of the rotary table is assumed to be on the table surface, and its origin coincides with the geometrical centre of the table. The surface is assumed to be a perfect plane, and the table has an ideal cylindrical shape.

The possible misalignments for the rotary table with respect to the robot base are:

- *Table offset*: the position of the rotation centre of the table does not coincide with the designed position in the robot's World reference frame $X_0 Y_0 Z_0$. The offset is expressed in Cartesian coordinates, as (dx, dy, dz).

- *Table external tilt*: the rotation axis of the table d_R is not parallel to the *Z* axis of the robot base. It is named *external* or *outer* in order to differentiate it from the internal tilt, discussed below.

In order to perform the tilt correction, one has to know the expression of the unit vector of the rotation axis d_R^0, expressed in $X_0Y_0Z_0$ reference frame. A rotation matrix R^{out}_{tilt} that transforms the vector $Z = [0, 0, 1]^T$ into d_R^0 has to be computed. Let the axis of rotation be perpendicular on the two vectors:

$$a^{out}_{tilt} = Z \times d_R^0 \tag{6}$$

and let the rotation angle be computed with the dot product:

$$\varphi^{out}_{tilt} = \arccos(Z \cdot d_R^6) \tag{7}$$

With these notations, the corrected reference frame is named $X_{R1}Y_{R1}Z_{R1}$, and the transformation matrix from the rotary table to the robot base is:

$$T_0^{R1}(\theta_R)' = T\,(500 + dx, 0 + dy, 200 + dz) \cdot R_{a^{out}_{tilt}}(\varphi^{out}_{tilt}) \cdot R_Z(\theta_R) \tag{8}$$

The table position is corrected with the Cartesian offsets, and the rotation around *Z* is pre multiplied with the tilt rotation matrix $R^{out}_{tilt} = R_{a^{out}_{tilt}}(\varphi^{out}_{tilt})$.

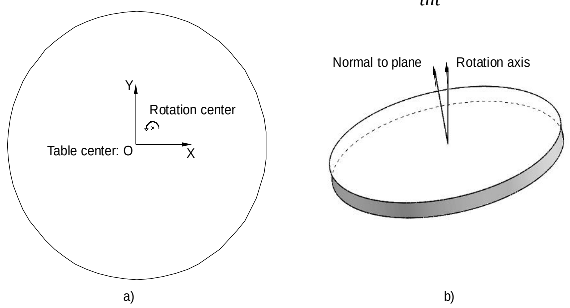


Fig. 5. Internal misalignments for rotary table

There may also be some misalignments present in the rotary table mechanism itself. The misalignments expected to be present, called *internal mechanical errors of the table,* are:

- *Table eccentricity* (Fig. 5*a*): the centre of rotation does not coincide with the centre of the table, on the table surface. The centre of rotation has the coordinates $(e_x, e_y, 0)$ on the table surface, in $X_RY_RZ_R$. The table shows oscillations in *XY* plane while rotating.
- *Table internal tilt* (Fig. 5*b*): the axis of rotation does not coincide with the normal to the table surface, which is plane. Therefore, the table shows oscillations in *Z* direction at its borders, while rotating.

These two internal misalignments are expected to be very small, but because the scanning system has to be accurate, these errors may influence the alignment process.

Table eccentricity is corrected by using the offsets dx' and dy', which depend on the rotary table angular position θ_R:

$$\begin{aligned} dx' &= dx - e_x \cos\theta_R + e_y \sin\theta_R \\ dy' &= dy - e_x \sin\theta_R - e_y \cos\theta_R \end{aligned} \tag{9}$$

The internal tilt is corrected using a rotation matrix R^{in}_{tilt}, which transforms the normal to the table surface corresponding to $\theta_R = 0°$, N_0 into the table rotation axis d_R^{R1}, where the vectors are expressed in the table reference frame $X_{R1}Y_{R1}Z_{R1}$.

$$a^{in}_{tilt} = N_0 \times d_R^{R1} = N_0 \times Z \tag{10}$$

$$\varphi^{in}_{tilt} = \arccos(N_0 \cdot Z) \tag{11}$$

The fully corrected reference frame is named $X_{R2}Y_{R2}Z_{R2}$, and the corresponding transform is:

$$T_0^R(\theta_R)^2 = T\,(500 + dx', 0 + dy', 200 + dz) \cdot R_{a^{out}_{tilt}}(\varphi^{out}_{tilt}) \cdot R_Z(\theta_R) \cdot R_{a^{in}_{tilt}}(\varphi^{in}_{tilt}) \tag{12}$$

The *robot – rotary table calibration* can be defined now as the procedure of computing the calibration parameters *dx*, *dy*, *dz*, a^{out}_{tilt}, φ^{out}_{tilt}, e_x, e_y, a^{in}_{tilt} and φ^{in}_{tilt}.

4.2. Error analysis

The main source of errors in this setup is given by the angular errors, either in encoder readings or axis misalignments, because a very small error in the angle leads to a large error in the location. For example, a 0.01 degree error in the first robot joint leads to an error of 0.15 mm when the arm is fully extended (worst case).

The encoder resolution for each robot joint is better than $7 \cdot 10^{-5}$ degrees (the exact value is 5242880 counts per revolution), which translates to a worst case Cartesian error of 0.55 μm. This value is much smaller than the mechanical errors inside the robot, such as backlash or termic deformations, and much smaller than the laser scanner accuracy. The repeatability of the robot is 0.02 mm at constant temperature, according to the documentation.

The scanning accuracy is limited by the encoder resolution of the table (0.03°), which will translate to a Cartesian error of 27 μm at a distance equal to 100 mm from the center of the table in *XY* plane. This error is uniformly distributed, as it appears due to uniform encoder quantization.

4.3. Verification methods

This section presents some basic tests in order to verify whether the laser scanning system is well calibrated or not. The tests use the scanning table, without any other fixtures or work pieces attached.

Alignment test: This test verifies the alignment between the vector normal to the table surface and the Z_L axis of the laser probe. The test is performed by positioning the laser probe so that it looks down onto the table (see Fig. 6a). The measurement from the laser probe should indicate a straight horizontal line. The measurement should not change when the laser probe rotates around its Z_L axis or when it translates parallel to the table plane $X_R Y_R$ (Fig. 6b). Also, the measured points, transformed in $X_R Y_R Z_R$, should lie in *XY* plane (their *Z* component should be close to 0, and less than the accepted error level).

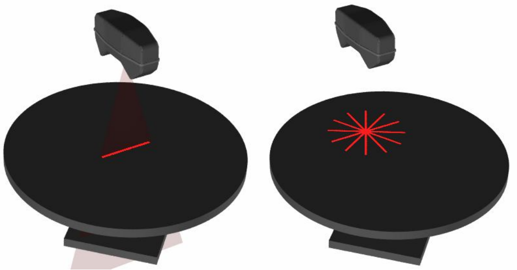


Fig. 6. Laser probe locations for alignment test

Note that if the *Z* component of the measured points is zero (or close to zero) this does not mean that the robot-laser calibration is computed correctly; it may be possible that the *dz* offset and the error in positioning the laser probe along the *Z* axis cancel each other. Therefore it is necessary to verify the offset with another method.

Eccentricity test: This test verifies the compensation for the internal mechanical errors (eccentricity and internal tilt) of the table.

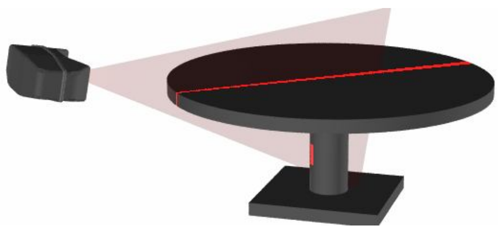


Fig. 7. Laser probe location for eccentricity test

The laser probe should be located like in Fig. 7, in order to be able to detect the table border and the table surface. The table performs a complete rotation and the laser probe is moved slightly by applying the calibration with Eq. (12)., so that it shouldn't change its position relative to the table. The measurements should not change, indicating that the and *internal tilt* and the *eccentricity* are corrected. In order to check only the *internal tilt*, the test can be also performed by placing the probe in one of the positions from Fig. 6, choosing a location close to the table edge.

Offset test. The test indicated in Fig. 6 is repeated for various angles around the table, and the measurements should remain the same. This indicates that the centre of the table, given by the offsets *dx* and *dy*, is correctly determined. The *dz* offset is also confirmed if the measured points on the table surface have their Z_R component equal to zero.

4.4. Parameter estimation

The calibration process starts with the ideal values of the transformations T_L^6 and T_0^R, from Eq. (3) and (4). When performing the *robot – table calibration,* it is assumed that the *robot – laser probe calibration* is correctly determined, therefore the laser probe can take readings and convert them into the robot reference frame, $X_0 Y_0 Z_0$.

The first step of robot – table calibration consists in determining the tilt values, both internal and external, so that the robot will be able to position the laser probe in a plane parallel to the table. A useful step in determination of the tilt values is measuring the normal vector to the table plane, described below.

4.4.1 Estimating the normal to the plane

A straightforward way to determine the equation of the table plane would be to gather a set of points which are not collinear, for example, to take two line measurements, with the laser probe looking onto the table, using *yaw* = 0° and *pitch* = 180°, like in Fig. 6a, from two different locations and/or roll values.

The two lines, whose expression can be found in $X_0 Y_0 Z_0$, determine a unique plane. For a better robustness to errors, the calibration routine may take a series of measurements all around the table, with different orientations. All the points gathered through this measurement sequence lie in a plane in $X_0 Y_0 Z_0$, which can be determined by solving a *least squares* problem (Dumitrescu et. al, 2006).

The accuracy in estimating the normals will give the performance of the scanning system for large objects (wide and/or tall). If a set of 100 points in a plane, uniformly distributed in *XY* plane on a circle having 300mm in diameter, and with a Z coordinate normally distributed with zero mean and 100 µm standard deviation, is used for computing the normal, its projection on the *XY* plane, which represent the error, is a 2D random variable, uncorrelated, with zero mean and $5 \cdot 10^{-6}$ mm standard deviation in any direction, which translates to an average angular error of 10^{-5} degrees. These results were obtained by computer simulation with pseudorandom input data.

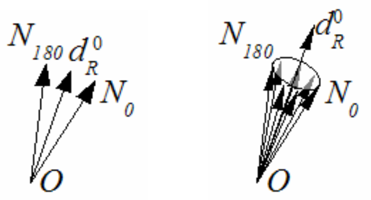
4.4.2 Determining internal and external tilt

In order to compute the internal and external tilt of the table, at least two normal vectors to the table have to be measured, the first corresponding to $\theta_R = 0°$ and the second corresponding to $\theta_R = 180°$. Let the two normal vectors, represented in $X_0Y_0Z_0$, be N_0 and N_{180}. By computing the average of the two vectors and normalizing the result (Fig. 8a), the axis around which the table rotates will be:

$$d_R^0 = \text{normalize}\left(\frac{N_0 + N_{180}}{2}\right) \qquad (13)$$

where $\text{normalize}(x) = x/\|x\|$.

For better noise immunity, more than two normal vectors can be measured, and they will determine a cone (Fig. 8b). The cone parameters are determined by fitting a plane through the vector extremities, and circle passing through the same points, in the above determined plane. The vector indicating the circle centre will be the axis of rotation for the table, d_R^0.



a) b)

Fig. 8. Determining the rotation axis: a) with 2 opposed vectors; b) with more vectors determining a cone

The calibration parameters a_{tilt}^{out} and φ_{tilt}^{out} can now be determined by replacing the estimated value of d_R^0 from Eq. (13) in Eq. (6) and (7). The orientation component of the partially corrected reference frame $X_{R1}Y_{R1}Z_{R1}$ can be computed by applying Eq. (8).

The vector representing the axis of table rotation d_R^{R1} can be expressed in $X_{R1}Y_{R1}Z_{R1}$ by applying T_0^{R1}, and the parameters a_{tilt}^{in} and φ_{tilt}^{in} can be computed with Eq. (10) and (11).

After applying the calibration parameters a_{tilt}^{out}, φ_{tilt}^{out}, a_{tilt}^{in} and φ_{tilt}^{in}, the laser probe is able to move in a plane parallel to the table surface. The other parameters which need to be estimated are the offsets *dx, dy, dz* and the eccentricity values e_x and e_y.

4.4.3 Determining offsets and eccentricity

The offset *dz* can be computed knowing that the points measured in the first step should lie in X_RY_R plane, therefore having their Z_R component equal to zero. A more realistic condition is that the random noise present in the Z_R components should have its mean value equal to zero.

As this measurement may be influenced by an incorrect estimation of the distance between robot flange and laser probe along the Z_L, the determination of the *dz* offset has to be confirmed by repeating the measurement by placing the probe like in Fig. 7. If the new measurement detects the points in X_RY_R plane, for various robot locations and orientations and various table angular positions, the offset *dz* has been correctly determined.

The remaining offsets, *dx, dy,* e_x and e_y indicate the table's centre in horizontal plane. The eccentricity can be expressed in polar coordinates too:

$$e_R = \sqrt{(e_x)^2 + (e_y)^2}\ ,\ e_\alpha = \text{atan}\,2(e_y, e_x) \quad (14)$$

The laser probe is located as in Fig. 7; the table turns with 360°. The table's vertical border will be detected as having an oscillating position in *XY* plane, with the amplitude equal to $2\,e_R$. The angle e_α can be observed by choosing the angle θ_R for which the horizontal position of the table border reaches its minimum and maximum values. To determine the circle's centre the laser probe is moved around the table in at least 3 locations, to acquire points from the table's border. A circle is fitted to the acquired points; its centre will indicate the offsets *dx* and *dy*.

5. Results and conclusions

The calibration and verification methods have been tested on the laser scanning simulation software described in (Borangiu, 2008a), which reproduces the behaviour of the laser probe (laser beam and optical sensors) located within a virtual 3D environment. The tests were successful, hence the above presented methods will be implemented and tested on the real system. An automatic calibration and validation routine will be developed using the above methods.

The expected accuracy of the scanning system is 50 μm standard deviation for medium objects, i.e. having 100 mm in diameter.

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