Calibration of Wrist-Mounted Profile Laser Scanning Probe using a Tool Transformation Approach

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Outline

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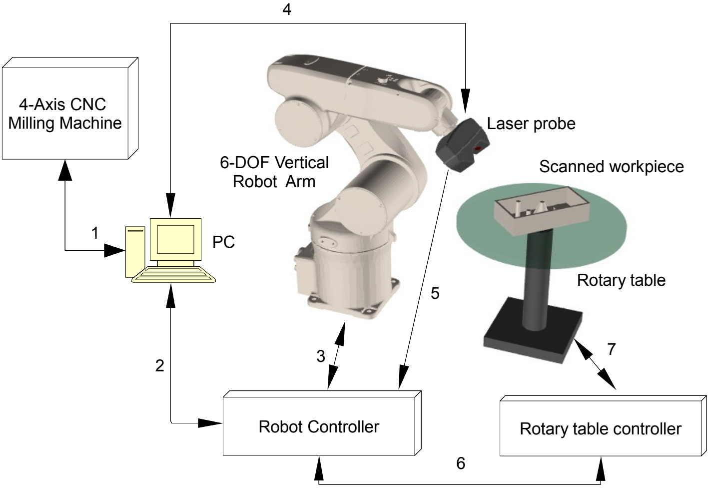
   - Previous Work
2. Calibration Method
   - Motivation
   - Principles
   - Verification methods
3. Results
   - A Simulation Result
   - 3D Reconstruction Example

Outline

3D Laser Scanning System Overview



Outline

Previous work on the Laser Scanning System

Simulator for the Laser Scanning System

- Simulates the profile sensor in a 3D virtual world, using a raytracing engine (POV-Ray)
- Simulates the robot motion, at kinematics level
- Can create a point cloud from simulated sensor data

Rotary Table Calibration

- Detects the position and rotation axis of the table only by pointing the sensor to the table surface
- Presented at RAAD 2008, Ancona, Italy

Outline

Motivation

Integration Issues

- The laser sensor was designed to be used in a CMM
- In the current system, it is mounted on a 6-DOF robot arm
- The calibration routines provided by the scanning software are not fully compatible with the current kinematics setup

Solution

- Reuse the part of the calibration which works properly
- Rewrite the calibration routines which do not work

Motivation

These calibration routines work

- Internal sensor correction parameters
- Compensation for misalignment between robot and sensor reference frames

They allow the sensor to be used in translation mode (X, Y, Z)

This calibration routine does not work

- Calibration of yaw, pitch and roll stages
  - the software tries to calibrate each stage separately.

Solution

Solution overview

- Move the Tool Center Point of the robot in the origin of the sensor's field of view (FOV)
- In this way, the sensor will be rotated around its origin
- The built-in calibration routines for the rotary stages (which didn't work) can be skipped

Advantages

- The sensor can be used in any desired orientation
- All the 3D data gathered by the sensor can be expressed in the reference frame of the robot

Outline

Ball Matching

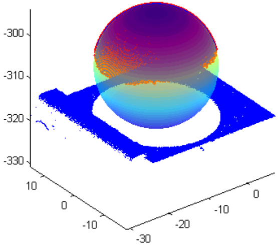
Sphere fitting - Riemann method (I)

- The data points are projected to a 4D paraboloid

$$t_i = x_i^2 + y_i^2 + z_i^2$$

- The new points lie in a hyperplane

$$t = ax + by + cz + d$$



Fitting scanned data points to a sphere

Advantage

The sphere fitting problem (nonlinear regression) was transformed into a hyperplane fitting problem (linear, much easier to solve)

Ball Matching

Sphere fitting - Riemann method (II)

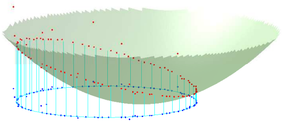
- A **robust** version of Least Squares is used to fit the hyperplane
- The hyperplane is projected back in 3D space ⇒ the fitted sphere

$$r = 1/2\sqrt{a^2 + b^2 + c^2 + 4\,d}$$

$$x_0 = a/2 \quad y_0 = b/2 \quad z_0 = c/2$$

Importance

- The Ball Matching calibration relies on the robust sphere fitting method



Circle fitting with the same method

Tool Transformation

Tool Transformation concept in Robotics

- Usually, the robot controls the position and the orientation of the end-effector mounting flange.
- The tool transformation allows moving the controlled reference frame anywhere on the end effector.

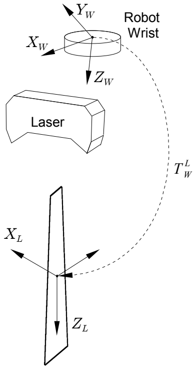
Internal Representation

- 4×4 homogeneous matrix
- Contains position and orientation data

Tool Transformation for the Laser Sensor

Roles of the Tool Transformation

1. Align the sensor to the axes of the robot's Tool coordinate system
   - The laser is mounted on the robot wrist with a rigid coupling
   - The axes of the sensor are not exactly parallel with the axes of the robot
   - Current setup: 0.5 degrees difference
   - Error at 200 mm: over 1.5 mm
2. Match the origin of the sensor's FOV with the origin of the Tool reference frame
   - The center of rotation becomes the origin of the laser FOV



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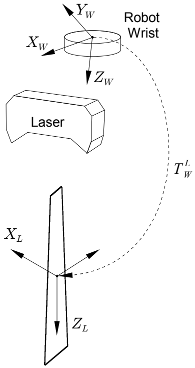

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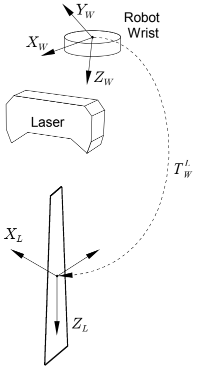


Computing the Tool Transformation (1)

Aligning the Laser Probe with the Robot

- This calibration routine is reused from the scanner software
- The ball is scanned from various positions, keeping the probe orientation constant
- Output data: 3×3 rotation matrix

- By default, the scanning software uses the rotation matrix to correct the 3D data from the sensor

Computing the Tool Transformation (1)

A slight modification in the reused calibration routine

- The 3D data from the sensor is left unchanged;
- Instead, the robot uses the rotation matrix to align the laser sensor with its axes;

Advantages

- No rotation will be applied to the 3D data!
- This also simplifies the reconstruction process!

Computing the Tool Transformation (2)

Finding the FOV origin relative to robot wrist

- The robot is now able to translate on the axes of the sensor
- It doesn't know the origin of the laser FOV, so it cannot rotate the sensor around a known point in space
- The ball is now scanned from different orientations
- The centers of the ball scans are computed and transformed into the World reference frame.
- Since there is the same ball, the sphere centers, expressed in World frame, should be identical.

Computing the Tool Transformation (2)

Finding the FOV origin relative to robot wrist

- The origin of the FOV (dx, dy, dz) is computed with respect to the mounting flange.
- At least 3 orientations are needed. This results in a linear system $(Ax = b)$ with A being 3×3 and $x = [dx\ dy\ dz]^{\mathrm{T}}$.
- For better accuracy, the ball can be scanned from more than 3 orientations. The system can be solved either using Least Squares, or a generic minimization procedure.

Outline

Visual Checks for Sensor Alignment

Alignment between the Z_{TOOL} axis and the sensor

- Place the laser beam perpendicular to a given surface
- Jog the robot along the Z_{TOOL} axis.
- The laser line should not move horizontally.

Alignment between the Y_{TOOL} axis and the sensor

- Place the laser beam perpendicular to a given surface
- Jog the robot along the Y_{TOOL} axis.
- The laser line should not translate in the X_{TOOL} direction.

Checking the Tool Center Point

The robot should rotate the laser probe around its FOV origin

- The probe is positioned with the ball exactly in the center of the field of view
- The profile detected by the laser is a circular arc, having the same diameter as the ball, and the center at $(0, 0, 0)$ in the sensor reference frame
- The laser sensor is rotated around the FOV origin in several directions
- The changes of the circular arc origin, as detected by the sensor, should be as small as possible

Outline

Ideal Tool Center Point location

- (60, 100, 200) milimeters

Orientations for the laser probe

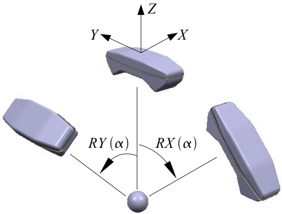
1. Vertical (downlooking)
2. Rotated around X with α
3. Rotated around Y with α

Measured position perturbed with

- Gaussian random noise on X, Y and Z
- Zero mean, 0.1 mm standard deviation

Monte Carlo simulation

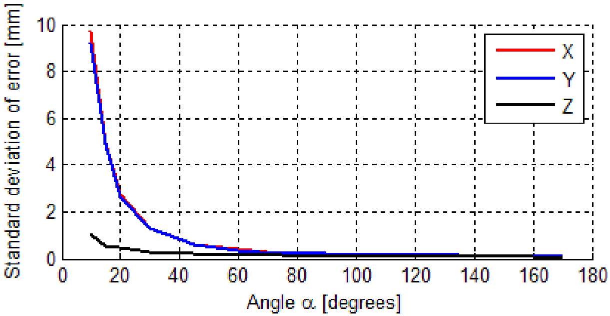
- 200 test runs for each value of α



Orientations for Ball Matching

Simulation results

- For small α, TCP estimation accuracy is *much worse* than the measurement accuracy
- The calibration works well for large values of α
- The residuals on Z have much lower magnitude than the ones on X and Y, for this particular choice of orientations



Outline

3D Reconstruction Example

Movie

Summary

- The paper presents the calibration between robot and laser sensor, with emphasis on finding the tool center point
- The calibration allows the sensor to scan the parts from any orientation
- Other applications become possible:
    - Accurate visual guidance using the laser sensor
    - 3D contour detection and following

References

Cignoni, Paolo et. al.
MeshLab: an Open-Source Mesh Processing Tool
Sixth Eurographics Italian Chapter Conference,
pp. 129-136, 2008.

Frühwirth R., Strandlie A. et al.
A review of fast circle and helix fitting
Nuclear Instruments and Methods in Physics Research,
vol. A 502, pp. 705-707, 2003.