Restoration of Rigid-Body Condition (RRBC) Method Illustrated

RRBC Method

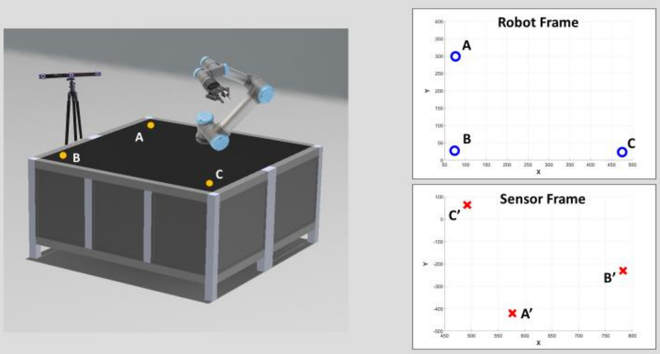
1. **Measure minimum of 3 registration points** with robot and sensor.
   - Registration points should be well distributed and encompass the work volume
2. Using any appropriate registration method, **determine transformation matrix (*R*, *t*)** that transforms registration points measured by sensor from sensor frame to robot frame.
3. **Identify points of interest (target points*)** within robot work volume.
4. **Identify points (fiducial points*)** around target points and measure them with sensor and with robot.
   - Ensure that region bounded by fiducial points encompass the uncertainty of the target point location.

*Target and fiducial points are explained later in the presentation

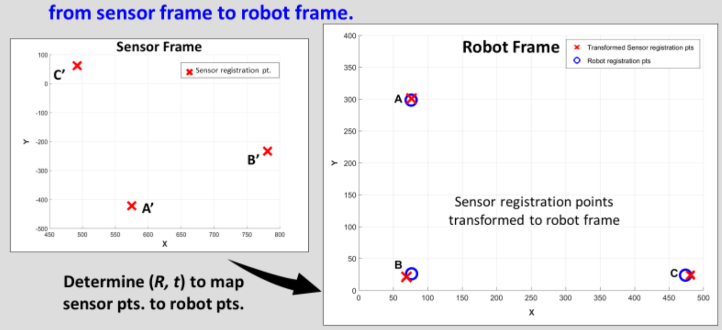
RRBC Method (continued)

5. **Apply inverse of transformation matrix $(R, t)^{-1}$** to fiducial points measured by the robot (from Step 4) transforming them from robot frame to sensor frame.
6. **Calculate differences** between transformed, robot-measured, fiducial points (from Step 5) and sensor-measured, fiducial points (from Step 4) to obtain corrections to sensor-measured fiducial points.
7. **Measure location of target points** with the sensor.
8. **Calculate and apply corrections** (from Step 6, using the fiducials closest to the target points) to the measured target points (from Step 7).
9. **Transform corrected target points** (from Step 8) from sensor frame to robot frame using (***R***, ***t***).

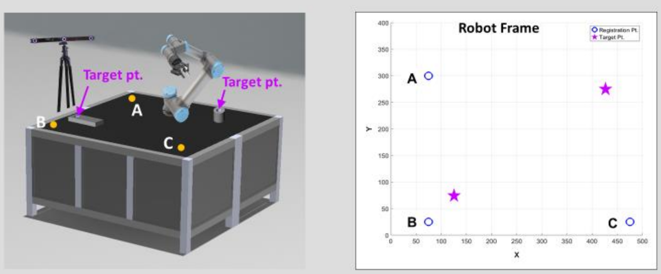
1. Measure a minimum of 3 registration points with robot and sensor.



2. Using ANY appropriate registration method, determine the transformation matrix (*R*, *t*) that transforms the sensor registration pts. from sensor frame to robot frame.



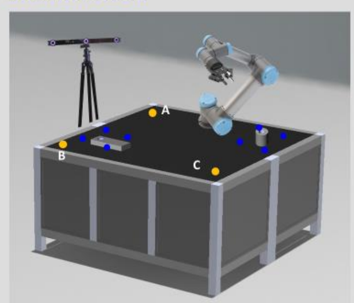
3. Identify points of interest (target points) within robot work volume.

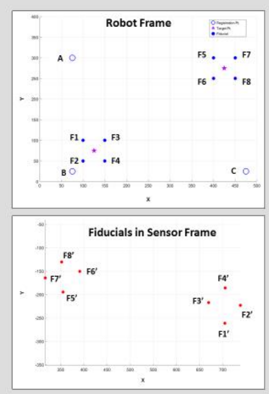


In this example, target points are hole locations where robot needs to insert a peg.

Generally, target "points" are centers of regions where robot needs to perform a task such as drilling, insertion, or assembly or regions where accurate location is required.

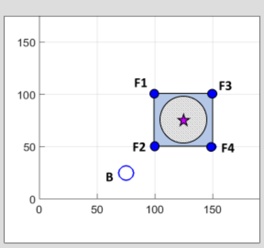
4. Select points (fiducial points) around target points. Measure their locations with sensor and with robot.





Selecting Fiducial Locations

Select location of fiducial points so that the region bounded by the fiducials contains the region of variability of the target point location. It is expected that there will be some variability in the target placement within the robot work volume.

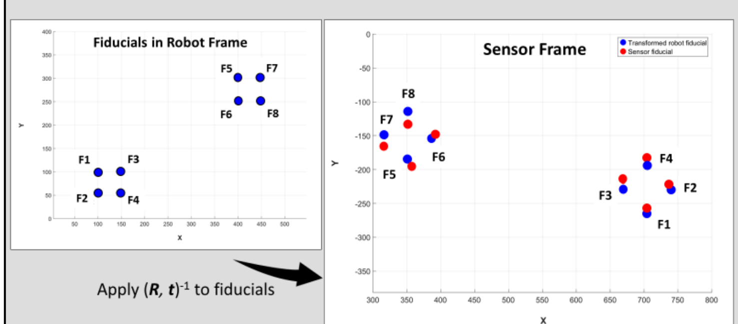


★ Nominal/expected location of target.

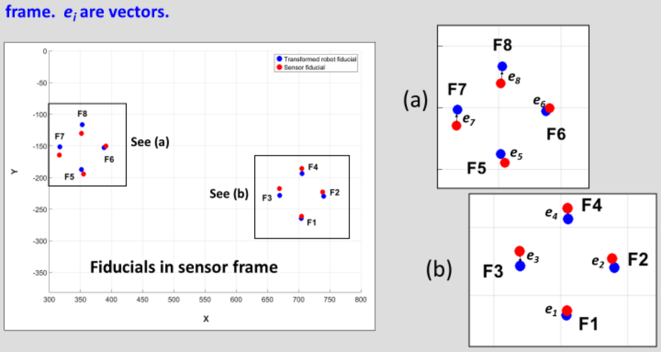
Region bounded by the fiducials.

Region of variability in the location of target point. That is, actual target location may be anywhere within this region.

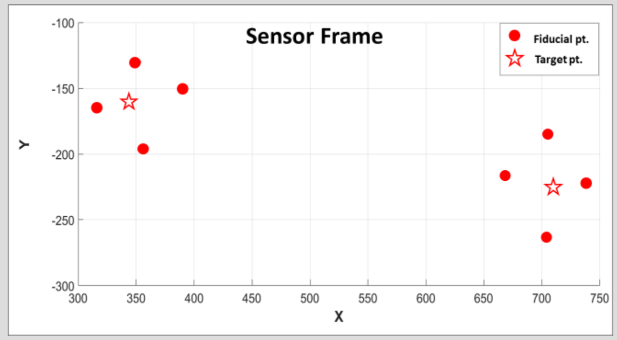
5. Apply the inverse of the transformation matrix $(R, t)^{-1}$ to robot-measured, fiducial points transforming them from robot frame to sensor frame.



6. Calculate differences between transformed, robot-measured fiducial points and sensor-measured fiducial points to obtain corrections, e_i, for fiducial points in sensor frame. e_i are vectors.

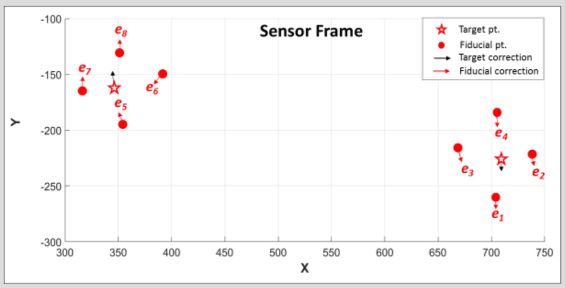


7. Measure locations of target points with sensor.



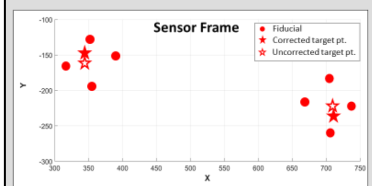
8. Calculate correction (using fiducials closest to target point) for the measured target point. Target corrections are linearly interpolated using fiducial corrections which are weighted based on their distance from the target point.

Apply correction to target point.

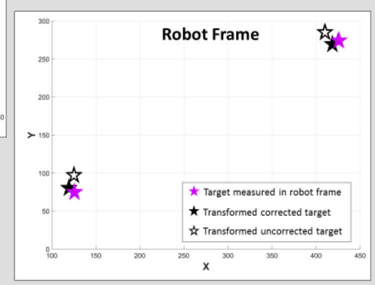


* Correction vectors exaggerated for illustration

9. Transform corrected target points from sensor frame to robot frame using (*R*, *t*).



Apply (*R*, *t*) to target points



* Uncorrected target points also transformed using (*R*, *t*) and shown only to illustrate the benefit of using RRBC method. Transformation of uncorrected target points would not be performed in actual practice.

Other methods to compensate for or reduce the positional error

- Active compliance control based on feedback from force/torque sensors
  - Involves a robot with this capability or the addition of hardware to obtain this capability
- Visual servo control
  - Involves image processing, computer vision, and robot control
- Volumetric Error Compensation methods
  - Discussed in next slide

RRBC vs. Volumetric Error Compensation (VEC) methods

RRBC	VEC
RRBC compensates for position error but does not require in-depth knowledge of the robot or sensor. Steps are easy to perform.	VEC models compensate for position error by using an analytical model that combines robot and sensor error. This requires in-depth knowledge of robot and sensor to compensate for potential sources of error. This is a challenging task.
If a different sensor is used with robot, interpolation scheme in RRBC method does not have to be modified.	If a different sensor (from the original sensor) is used with robot, VEC model needs to be updated.
Both methods require comparable amounts of data to be collected – to determine model parameters in VEC method and for the interpolation scheme in RRBC method.	

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