Boost Calibration for Dual-arm Co-robotic Ultrasound System

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Introduction

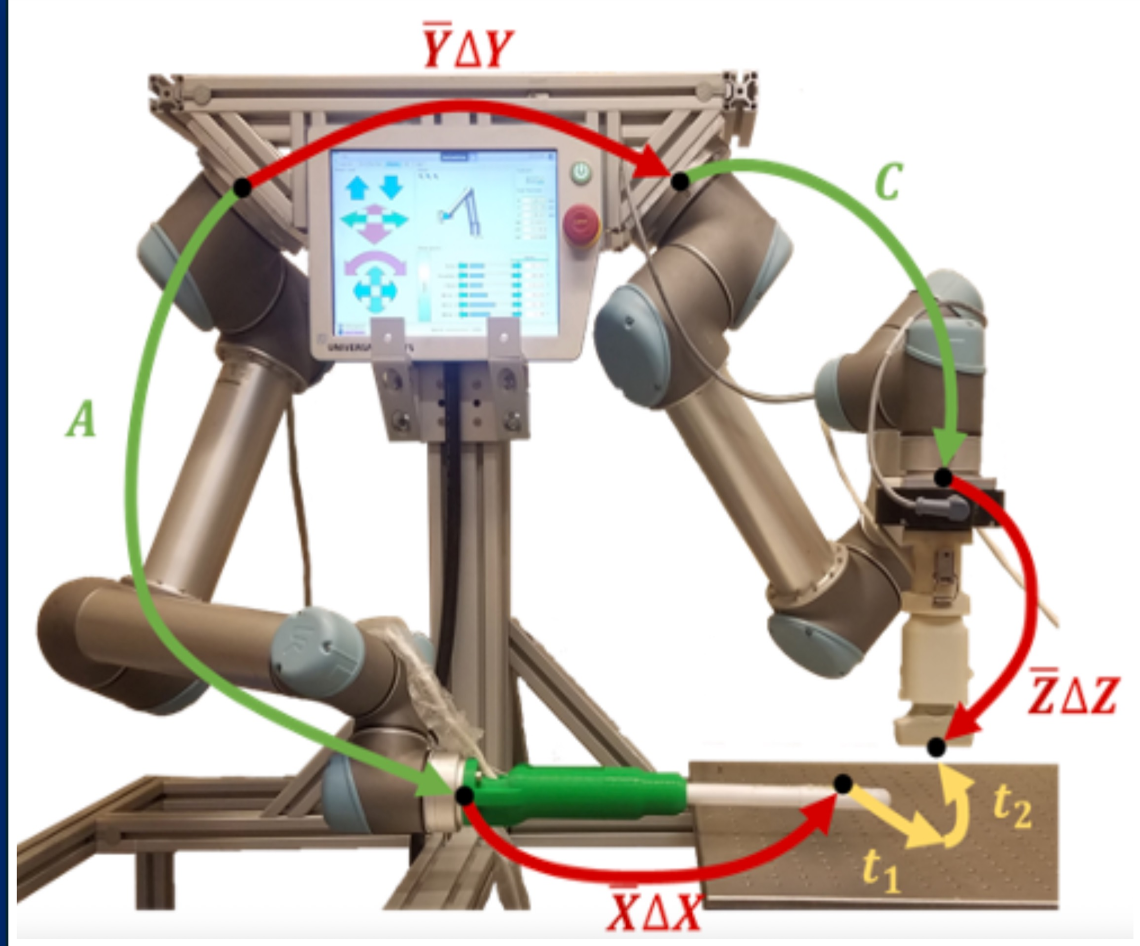
Clinical application
- Prostate cancer
- Ultrasound tomography (UST)

Challenges & motivation
- Dual robotic arm UST
- High calibration precision

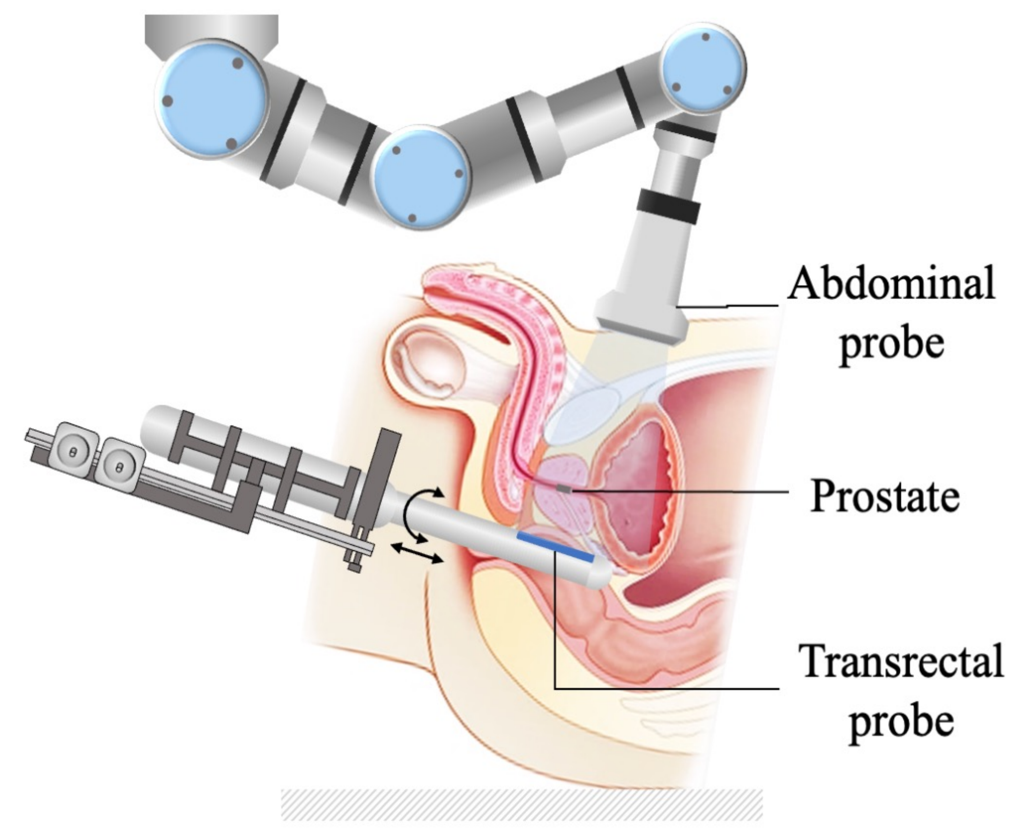
Previous works
- BXp Calibrates each arm
- Point cloud for base to base

Our proposal
- Boost calibrate based on primal calibration

System Setting



Dual-arm co-robotic ultrasound system



Clinical setup

Methods

- **Linearized system** $A\bar{X}\Delta X t_1 = \bar{Y}\Delta Y C\bar{Z}\Delta Z t_2$

with 21 unknown parameters and 3 constraints:

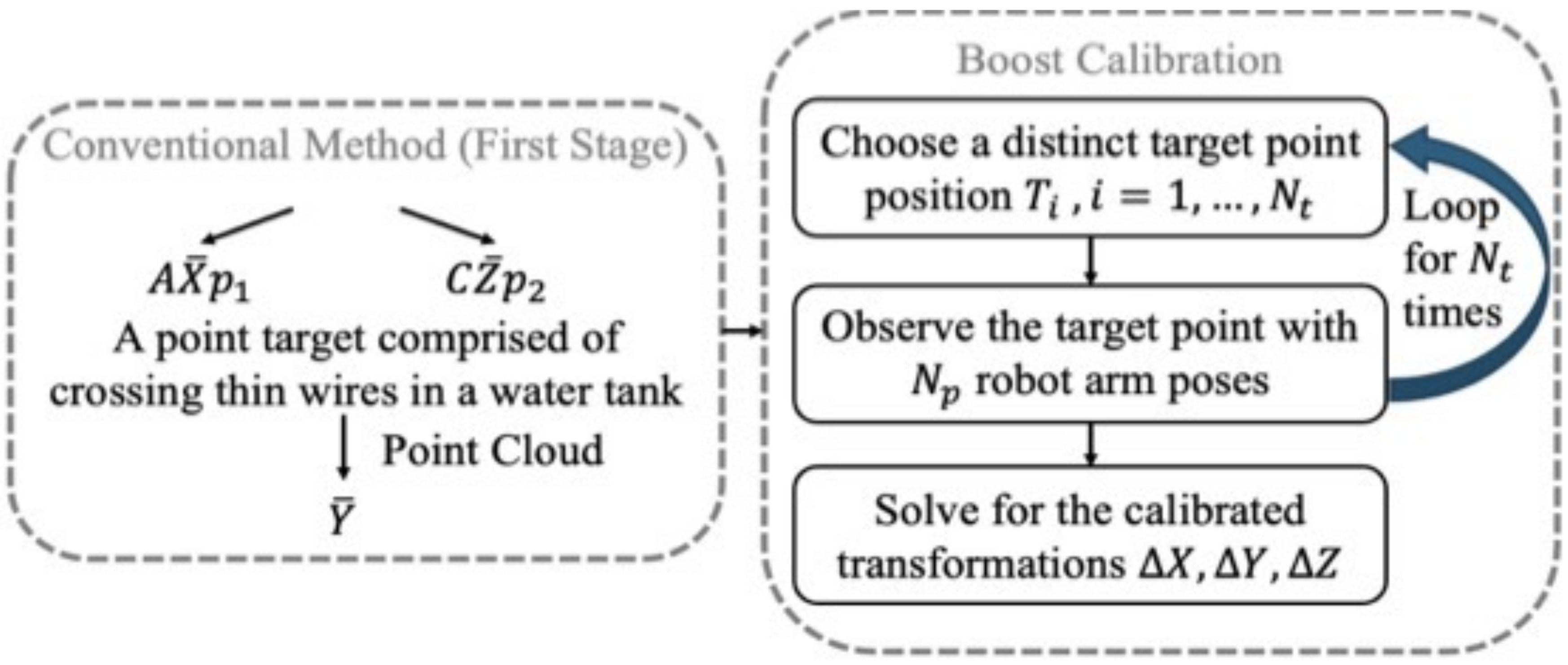
$$A_1\Delta a_X + A_2\Delta a_Y + A_3\Delta a_Z + B_1\Delta\theta_X + B_2\Delta\theta_Y + B_3\Delta\theta_Z + C_1\Delta p_X + C_2\Delta p_Y + C_3\Delta p_Z = D$$

Subject to $\Delta a_X \perp a_{\bar{X}}, \Delta a_Y \perp a_{\bar{Y}}, \Delta a_Z \perp a_{\bar{Z}}$,

where,

$$U := \bar{Y}^{-1}A\bar{X}, W := C\bar{Z}$$

$$A_1 = -R_U(t_1)^\wedge\theta_{\bar{X}}, A_2 = (R_W t_2 + p_W)^\wedge\theta_{\bar{Y}},$$
$$A_3 = R_W(t_2)^\wedge\theta_{\bar{Z}}, B_1 = R_U(a_{\bar{X}})^\wedge t_1,$$
$$B_2 = -(a_{\bar{Y}})^\wedge(R_W t_2 + p_W), B_3 = -R_W(a_{\bar{Z}})^\wedge t_2,$$
$$C_1 = R_U R_{\bar{X}}^{-1}, C_2 = -R_{\bar{Y}}^{-1}, C_3 = -R_W R_{\bar{Z}}^{-1},$$
$$D = -R_U t_1 - p_U + R_W t_2 + p_W.$$



- **Specification:** Multiple target points
  Mitigate ill-conditioned A_2), less Δa_Y noise sensitivity
- **Error estimation:** upper bound, fast, robust
- **Validation:**
  - ➢ Simulate error upper bound between desired and actual points, considering varying ultrasound noise levels
  - ➢ Simulate a clinical setup with dual 2D probes

Results

- 100 (10 x 10) poses and 5 target position:

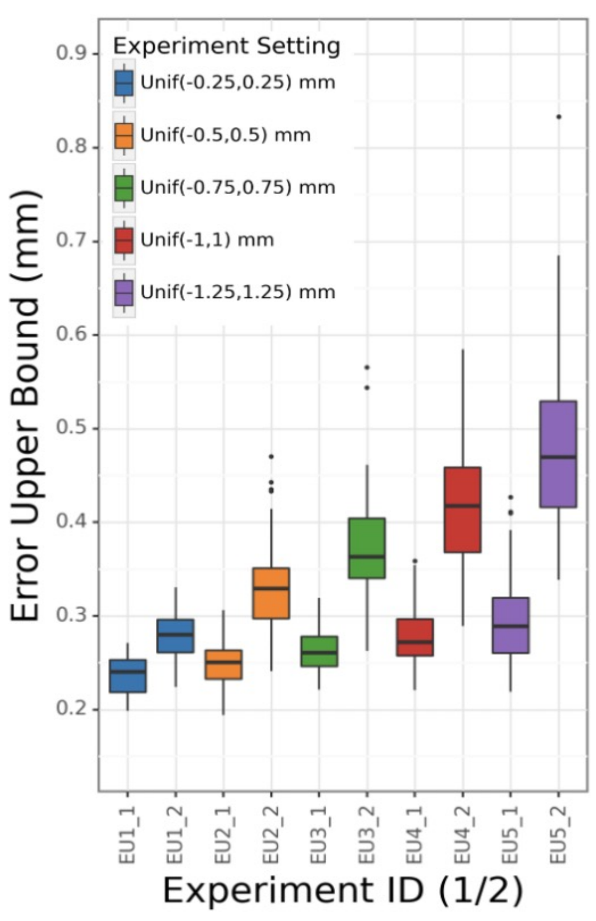
➢Without noise: **0.25mm**

➢With +-1 mm noise: **0.35mm**

Less that ½ image resolution **0.75mm** (1 MHz central frequency)

- "Boost" step increases calibration precision significantly

Pose component	First stage	Boost calibrated	
		A	B
Roll (degree)	1.0	2.8e-2	2.5e-3
Pitch (degree)	0.4	3.3e-2	2.1e-2
Yaw (degree)	1.1	1.2e-2	4.9e-3
Translation distance (mm)	3.5	1.3e-2	5.3e-3



$N_t = 7, N_p = 100$

Conclusion & Discussion

Summary
- Novel Boost Calibration for dual-arm UST
- High accuracy
- Robust to ultrasound noise
- Works with 2D data only

Limitation
- Calibration process is complex: requires multiple target points and robot poses
- Does not account for unreachable poses due to spatial or clinical constraints

Future work
- Test on real robotic system
- Apply to clinical prostate cancer imaging

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