Tissue Stiffness Predictive Admittance Control for Robot-Assistive Ultrasound Imaging

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Abstract

Robot-assisted ultrasonography can reduce operator dependence and physical workload, but safe imaging requires precise contact-force regulation during the transition from free space to tissue. We propose a predictive admittance architecture that combines surface and contact estimation, online tissue-stiffness adaptation, force-consistent target-depth prediction, and compliant normal-axis control. Experiments on a UR5e platform reached a stable **10.0 N** target, adapted to stiffness variations of **3000--5000 N/m**, and achieved **0.44 N RMSE**. The probe also executed a continuous 3D square-spiral scan with high planar repeatability.

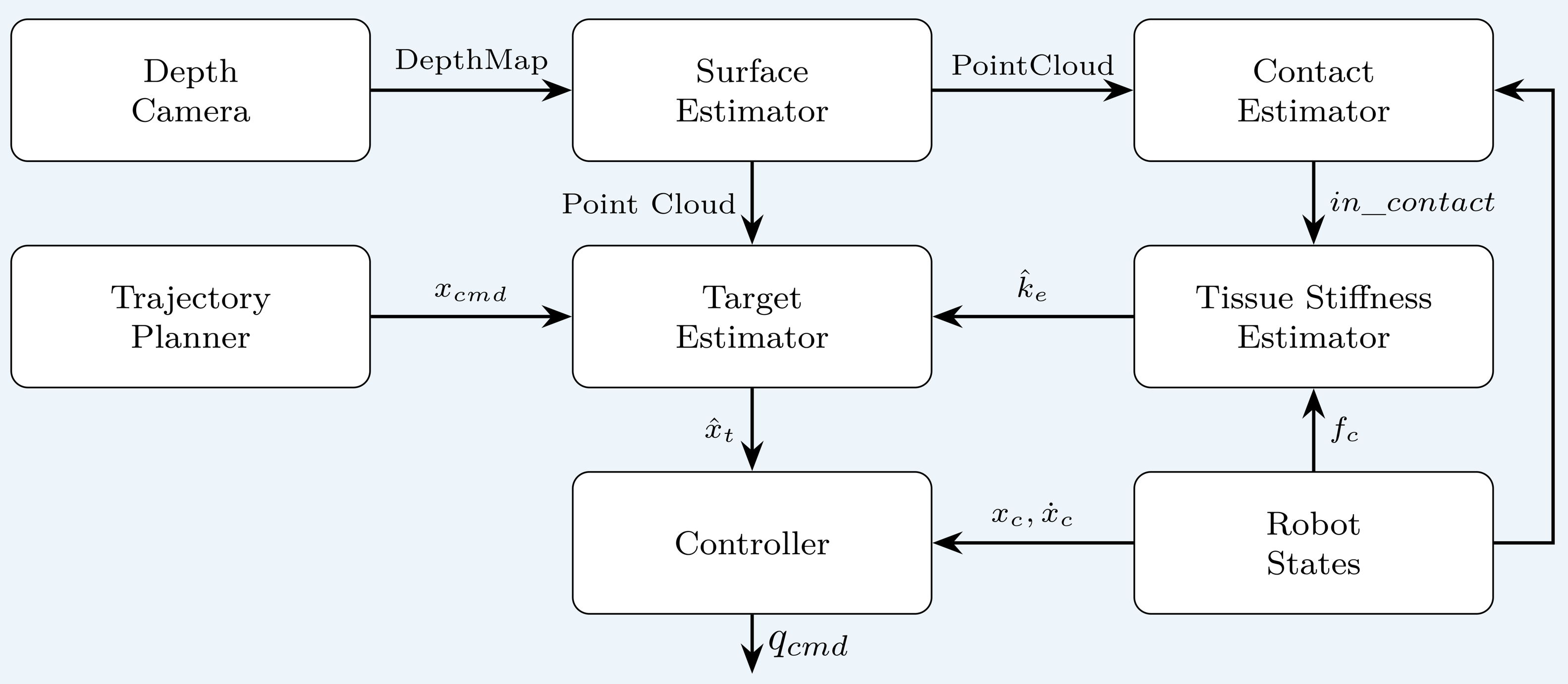
Main Contribution

This work proposes a **tissue-stiffness predictive admittance controller** for autonomous robotic ultrasound scanning. The controller regulates the surface-normal interaction while preserving planar scan execution.

- Online instantaneous tissue-stiffness estimation from measured contact force.
- Force-consistent target-depth prediction before large force error accumulates.
- Discrete-time admittance control with velocity-limited target updates.
- Experimental validation on a UR5e robotic ultrasound platform.

Control Architecture

The controller separates perception, contact recognition, stiffness adaptation, target-depth prediction, and admittance control.



Design principle: predict the force-consistent target depth and let admittance dynamics move the probe smoothly toward it.

Predictive Stiffness and Target Estimation

During active contact, instantaneous tissue stiffness is updated from the sensed-to-target force ratio:

$$\hat{k}_{e,inst} = \hat{k}_{e,prev}\left(\frac{f_{c,sensed,z}}{f_{target,z}}\right).$$

Sensor noise and abrupt numerical changes are suppressed using an exponential moving average:

$$\hat{k}_e = (1-\alpha_k)\hat{k}_{e,prev} + \alpha_k \hat{k}_{e,inst}$$

where, $\alpha_k = 0.001$.
The force-consistent target depth is predicted as

$$\hat{x}_{t,z,raw} = x_{n,z} - \frac{f_{target,z}}{\hat{k}_{e,z}}.$$

The target update $\Delta x_{t,z}$ is velocity-limited before application, preventing discontinuous depth jumps during contact transition.

Admittance Control Law

The normal-axis error is defined relative to the predicted target:

$$e_{x,z} = x_{c,z} - \hat{x}_{t,z}.$$

The compliant acceleration follows

$$\ddot{x}_{c,z} = M^{-1}\left(-B\dot{x}_{c,z} - K_{t,z}e_{x,z}\right)$$

where, $M = 1,\ B = 200,\ K_t = 200.$
With $\Delta t = 0.002\,\mathrm{s}$, semi-implicit Euler integration gives

$$\dot{x}^{+}_{c,z} = \dot{x}_{c,z} + \ddot{x}_{c,z}\Delta t.$$

The updated normal velocity is combined with the planned planar velocity $v_{xy,t}$, then mapped to the robot joints:

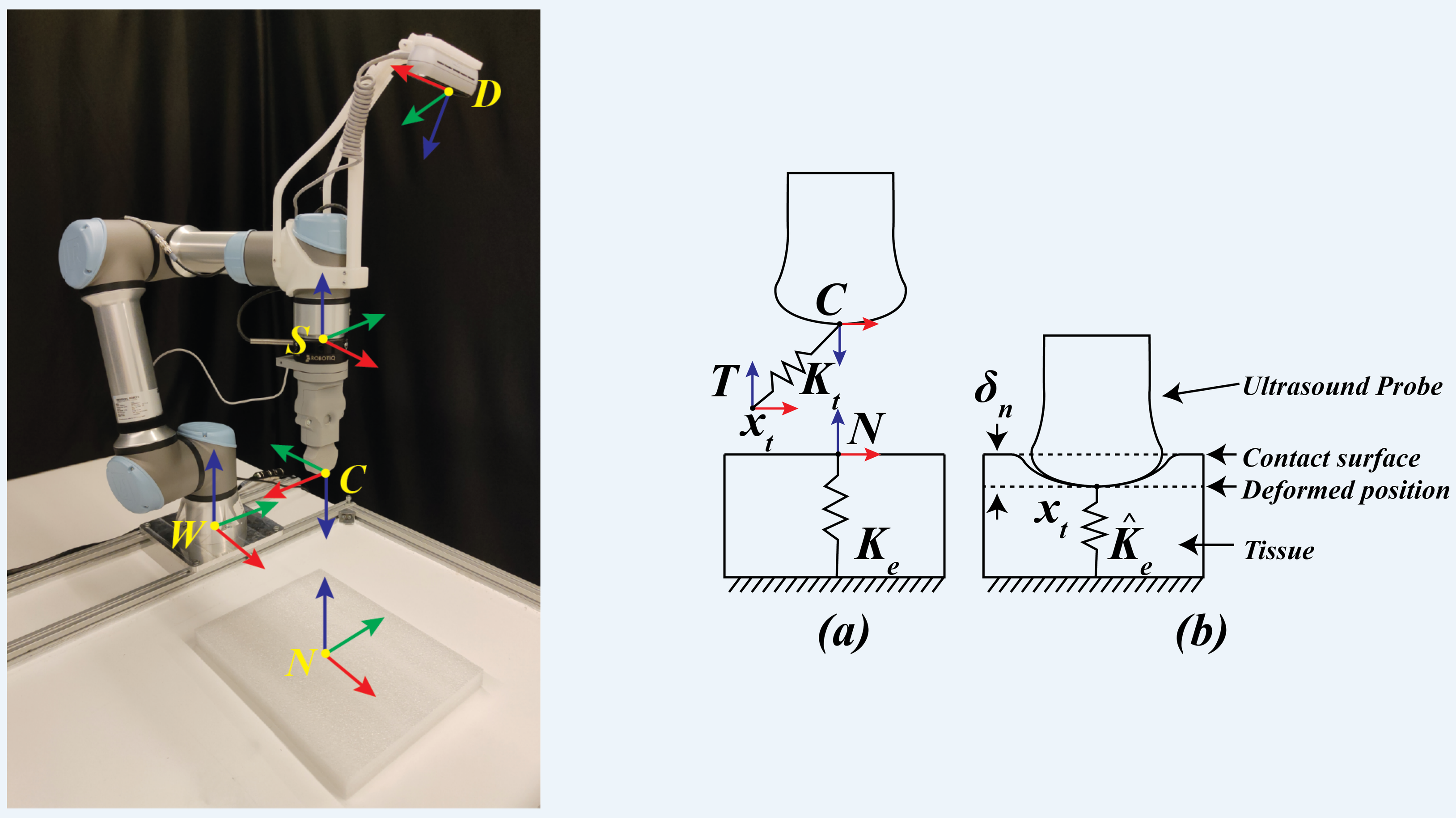
$$\dot{q} = J_c^{+} v_{cmd}$$
$$q^{+}_{cmd} = q_{cmd} + \dot{q}\Delta t$$

Surface Contact and Tissue Model

The surface estimator extracts a local anatomical profile. The nearest surface point is denoted $\{N\}$, and normal penetration is evaluated by

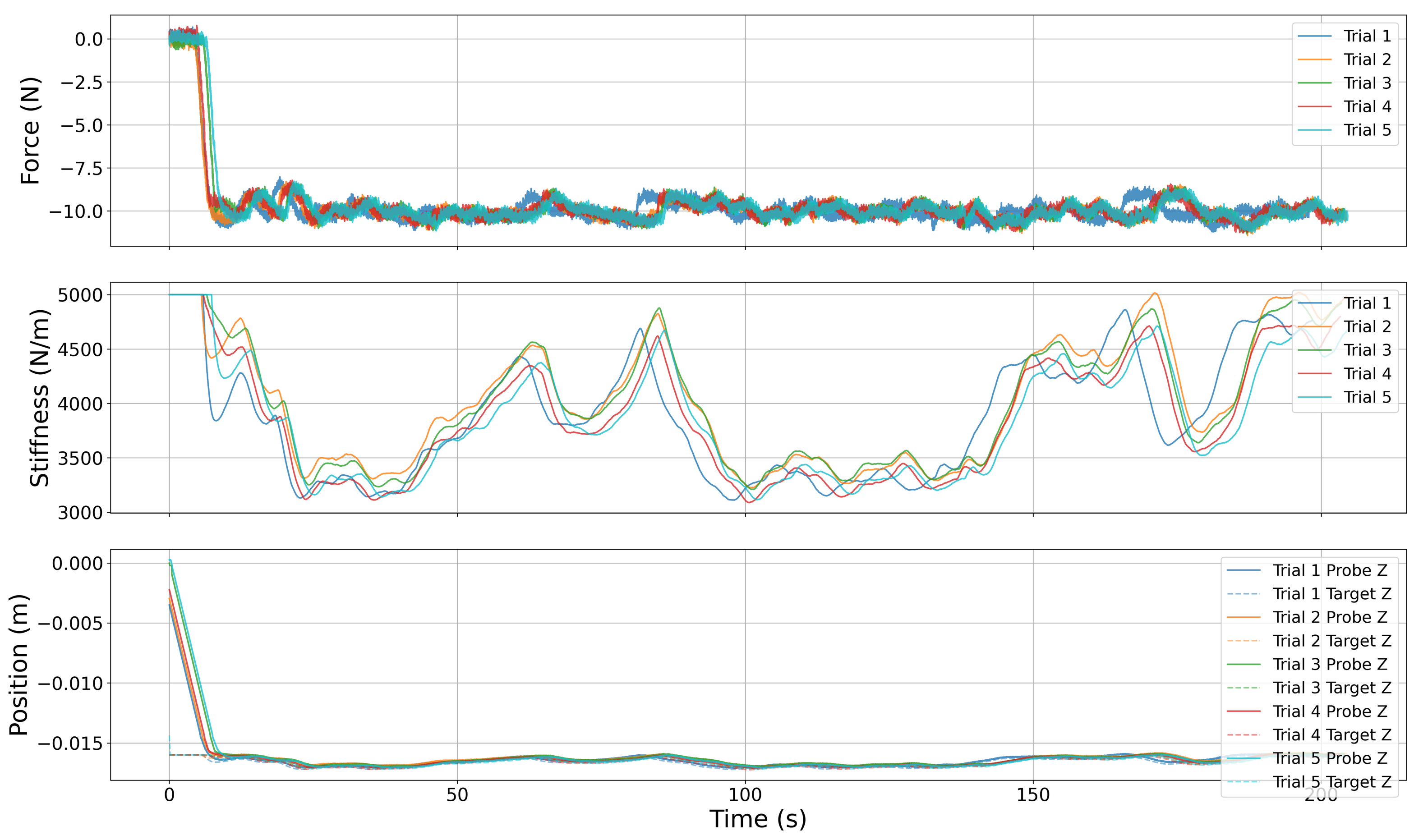
$$\delta_n = x_{c,z} - x_{n,z}.$$

An active contact state is declared when, $\delta_n \leq 0$.

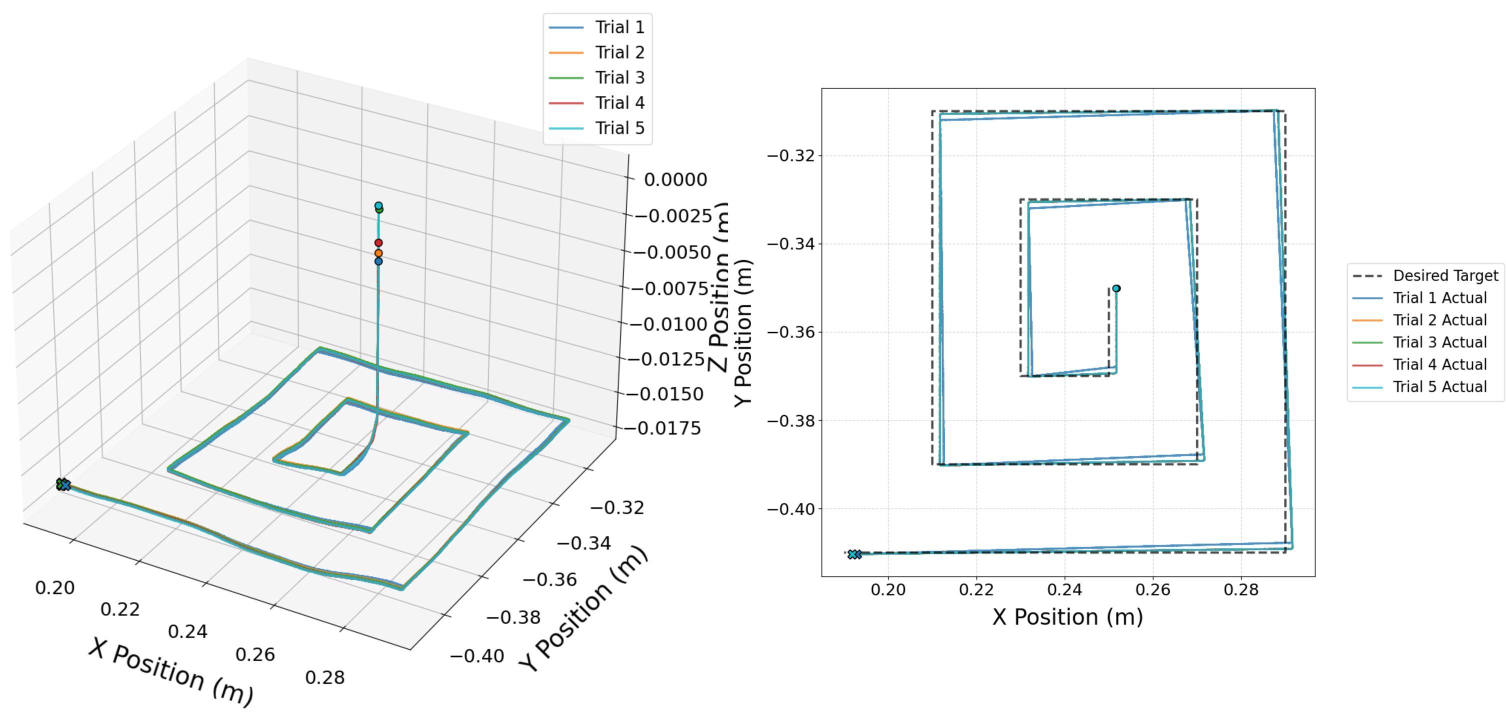


Interpretation: the target estimator replaces a direct integral force term by moving the reference coordinate $\hat{x}_t$ toward a force-consistent interaction depth.

Key Results



- Smooth transition from free space to the **10.0 N** target force across five trials.
- Online stiffness adaptation captured tissue resistance changes from **3000 N/m** to **5000 N/m**.
- After the 15 s stabilization phase, force tracking reached **0.44 N RMSE**.



- The probe completed a continuous 3D square-spiral trajectory with active normal-axis depth regulation.

Conclusion and Future Work

Conclusion: The proposed predictive admittance controller achieved stable contact transition, maintained a 10.0 N target force with 0.44 N RMSE, adapted to stiffness variation, and executed repeatable 3D scanning.

Future work: extend normal-axis compliance to multi-axis translational/rotational compliance, integrate soft-body contact mechanics and pressure distribution, and improve real-time dynamic surface estimation from depth-camera point clouds.

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