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Needle localization for needle steering under 3D ultrasound feedback

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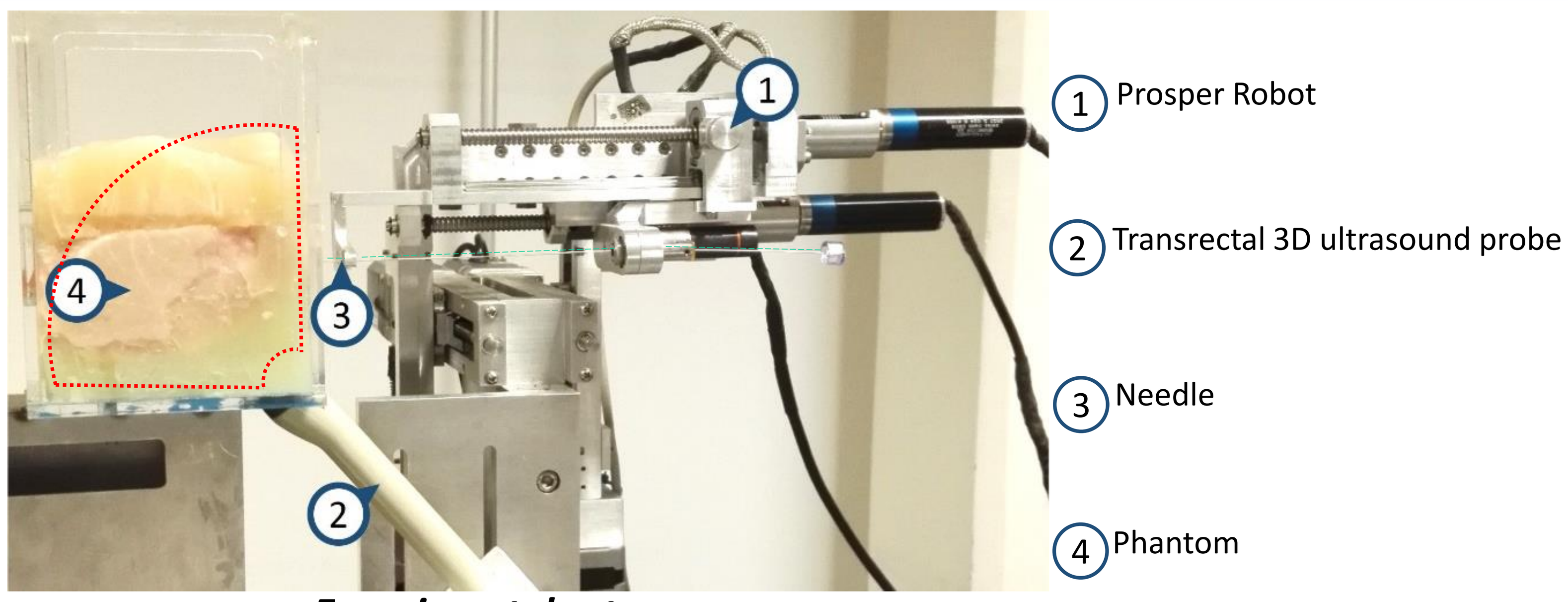
Introduction

Motivation and objectives

- In needle steering, estimating the needle pose is a critical problem
- In 3D ultrasound volumes, fine needle localization is difficult and requires a combination of estimation and image processing to be successful. Indeed, 3D ultrasound imaging suffers from noise, artifacts and works at a low frequency
- We propose a needle tip pose estimation method in the context of 3D robotic needle steering under 3D ultrasound feedback, based on multi-rate, multi-sensor fusion [1]
- This estimation feeds a segmentation algorithm for robust needle detection



Experimental setup

Tools

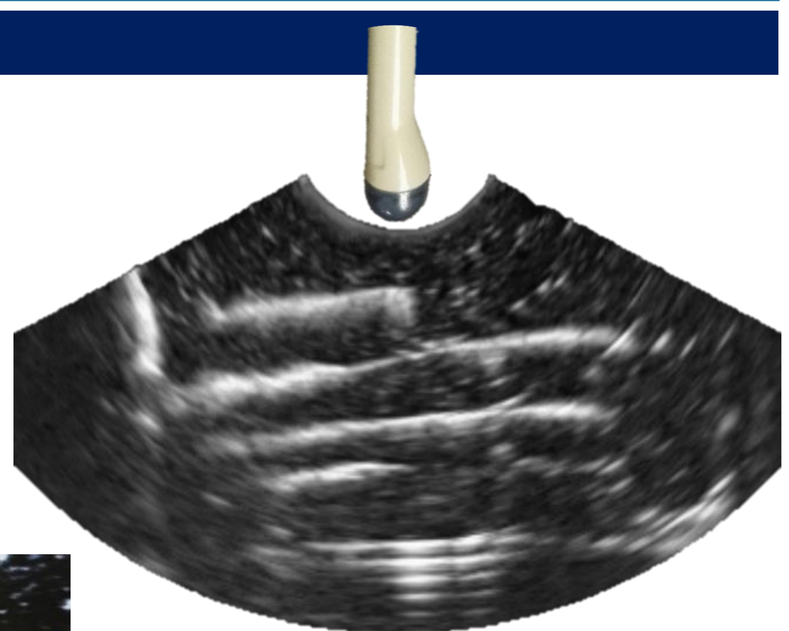
Robotic device

- PROSPER robot for brachytherapy procedure [2]
- 6 degrees of freedom, needle insertion and rotation module

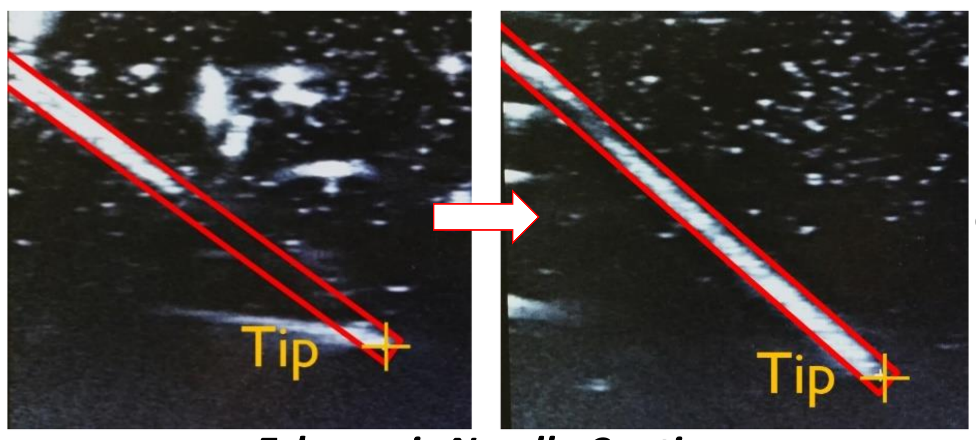
Ultrasound (US) imaging

3D US imaging in B-mode

- 3D B-mode US volume @ 1Hz
- 3D end-fire probe 4DEC-9/10 with Ultrasonix Sonix RP US system



Slice of 3D US volume

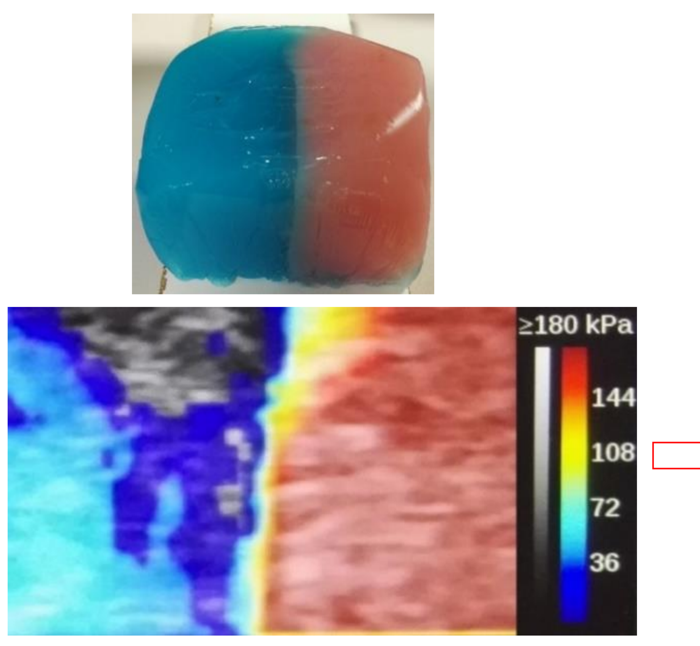


Echogenic Needle Coating

- Needle-related artefacts appear such as comet tail artefacts, reverberation etc.

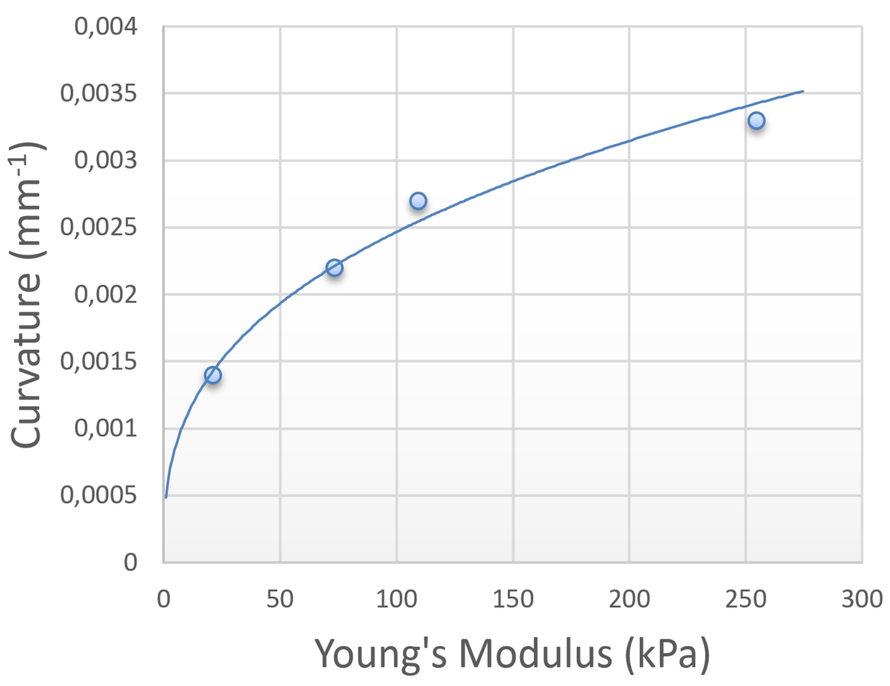
Pre-operative shear wave imaging (SWE)

- SWE estimates tissues Young's modulus from their response to a shear wave US stimulation
- The needle curvature is proportional to the tissue stiffness



Bi-layered Agar phantom and associated SWE

The red part is stiffer than the blue one

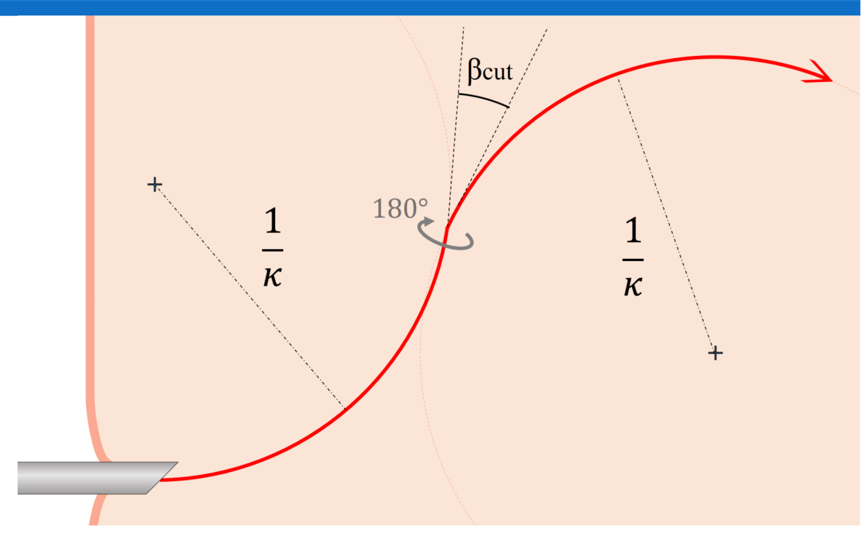


Needle curvature dependency to tissue stiffness

Methods

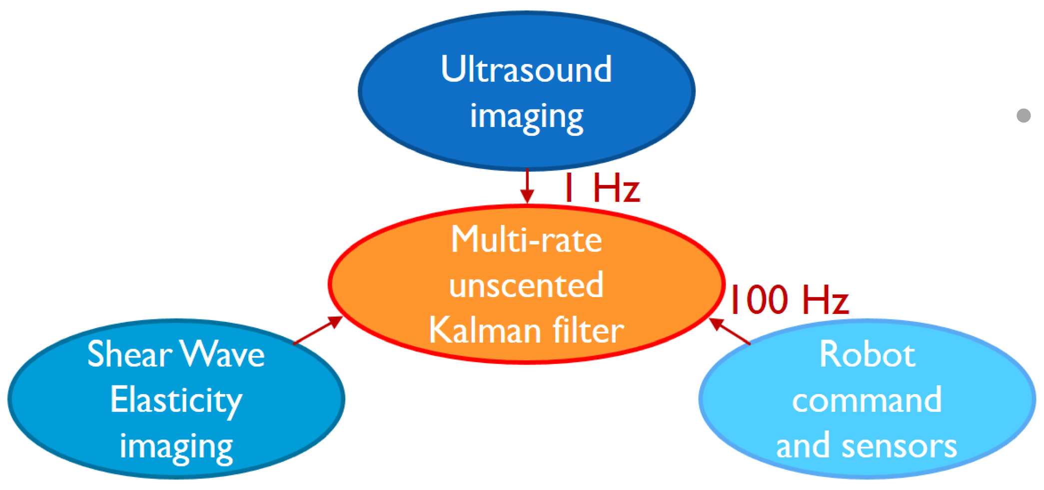
3D kinematic bicycle model

- The needle tip path is modeled by a bicycle kinematic model [3]
- β_{cut} is the cutting angle of the needle, as deduced from data fitting



Multi-rate unscented Kalman filter

- The needle tip pose and curvature are estimated by a multi-rate unscented Kalman filter
- All available measurements are taken into account asynchronously



- The filter updates the estimation error covariance online to account for poor 3D US quality and expected changes of tissue stiffness

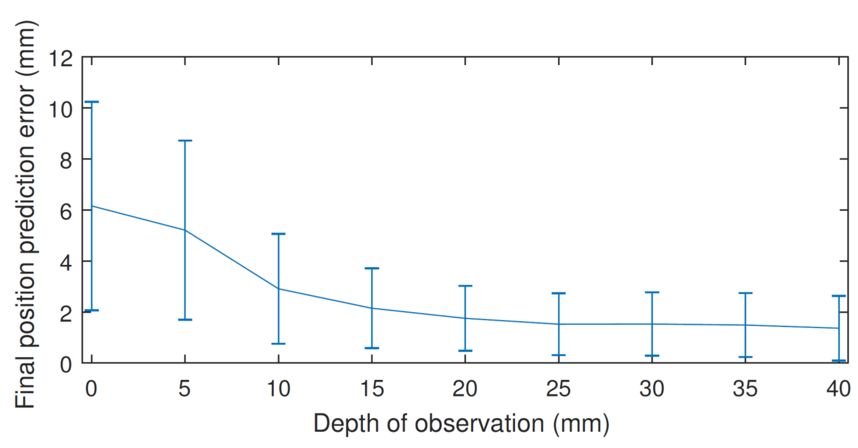
Results

- 51 insertions of 8 cm at 1.5 $mm.s^{-1}$
- Validation on phantoms and ex vivo tissue sample

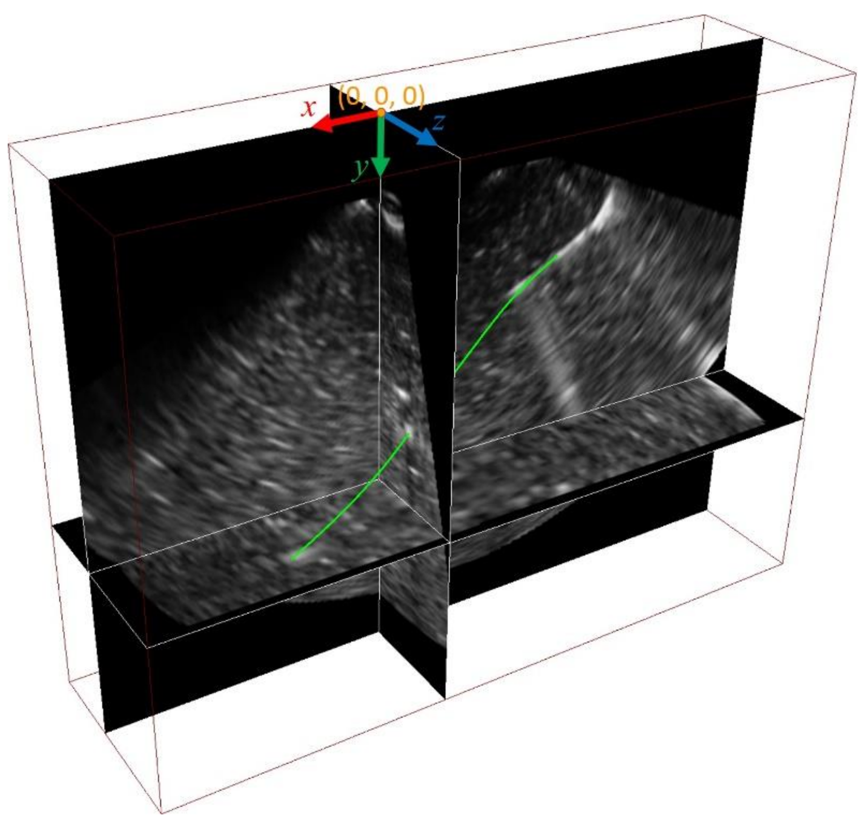
Medium	Needle	$E_{mean}(mm)$	$E_{std}(mm)$	$E_{max}(mm)$
Agar	S-BT	0.5	0.3	1.9
Agar	N-BT	0.6	0.3	2.6
Paraffin	S-PC	0.6	0.4	6.0
Pork	N-BT	0.7	0.3	1.7

Needle tip localization error

N-BT : Nitinol bevel-tip S-PC : Steel pre-curved



Needle tip final position prediction



Needle tip path estimation (green) in the last acquired 3D US Volume

Conclusion

- The tip pose estimation is accurate, robust to needle disappearance and 3D ultrasound imaging artefacts
- An adapted segmentation method, inherited from [4], uses the resulting ROI for needle tip segmentation in the 3D US volumes
- The good estimation of the tip behavior and its uncertainties could benefit to adapted control laws and path planning methods

References

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