Hydrophone Sensor Integrated with APL Snake Robot

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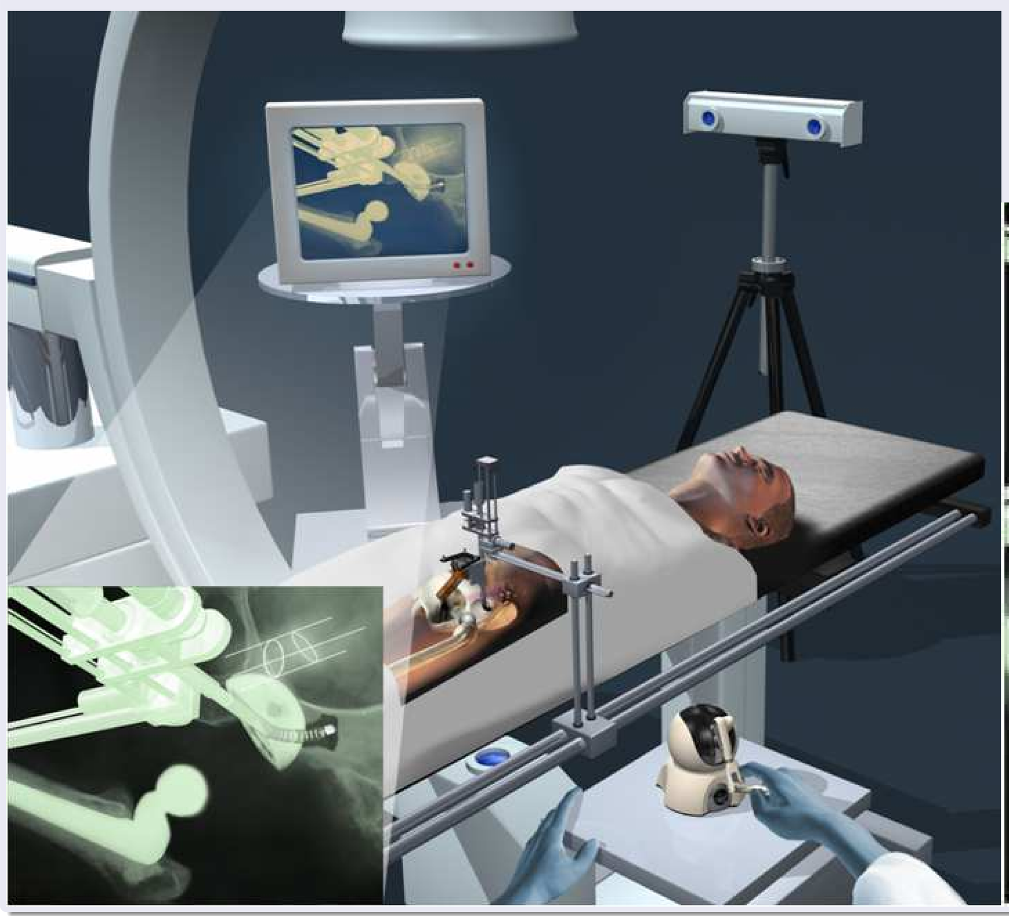
The Problem

The APL Snake robot has a highly dexterous end manipulator and is intended to be used in the surgical removal of osteolytic bone from a cavity formed behind the cap of a hip implant. However, there is a need to accurately track location of the end manipulator, as an accuracy of only 1.3 mm can be achieved with kinematic prediction alone, and this may worsen wth more complicated designs.



Solution

We intended to integrate an optical hydrophone into an inner lumen of the APL Snake robot and use the time-of-flight of ultrasound signals from an external probe to locate the manipulator tip through multilateration.

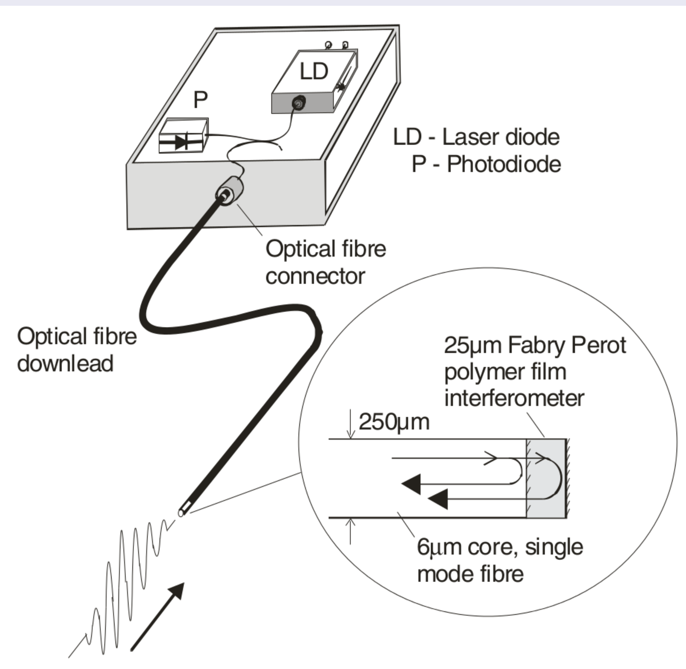


Figure: B T Cox et al.

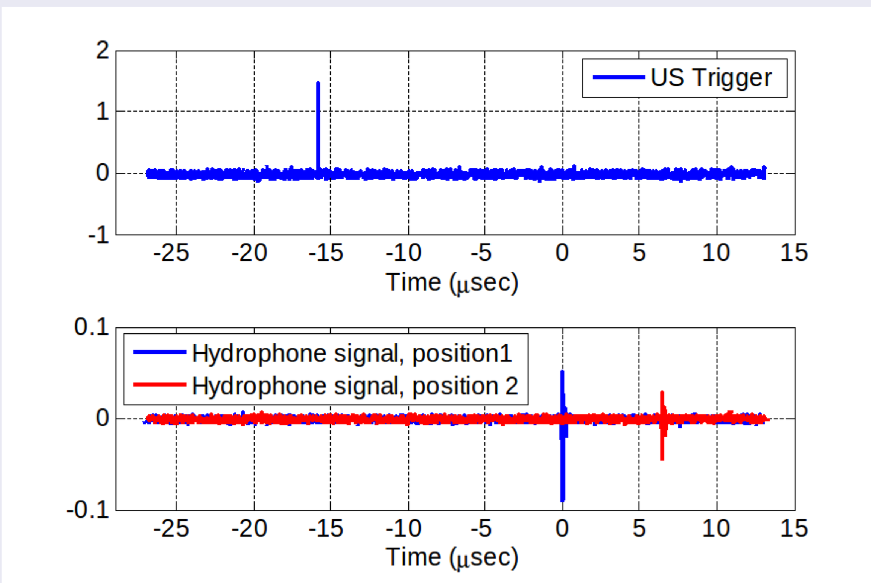
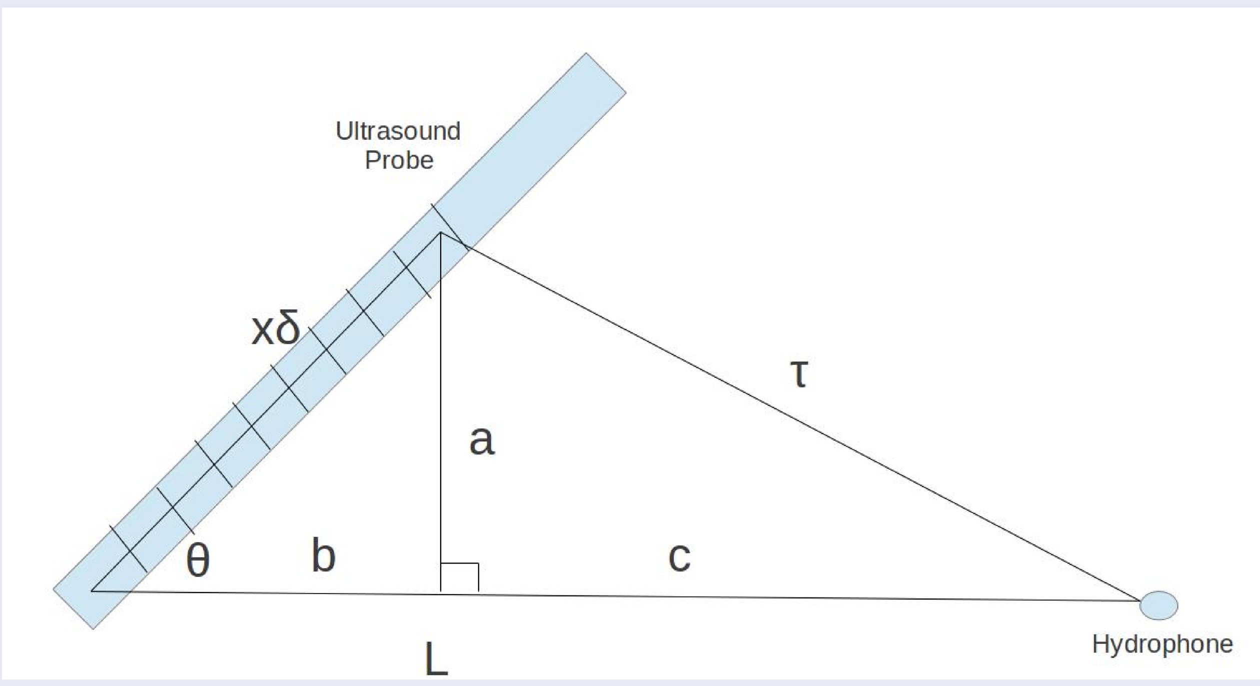


Figure: B T Cox et al.

Preprocessing

We take advantage of probe geometry to get more accurate measurements and to estimate the probe parameters including the spacing between piezoelectric elements.



Define:

1. x: Zero-based index of piezoelectric element
2. δ: Spacing between each element
3. L: The distance between the hydrophone and first element
4. θ: The angle the probe makes with the line between hydrophone and first element
5. τ: The distance to element x as calculated by time of flight

$$\tau^2 = a^2 + c^2$$
$$L = b + c$$
$$a = x\delta \sin\theta$$
$$b = x\delta \cos\theta$$

$$\begin{aligned}\tau^2 &= a^2 + c^2 \\ &= (x\delta \sin\theta)^2 + (L - b)^2 \\ &= x^2\delta^2 \sin\theta^2 + L^2 - 2Lx\delta\cos\theta + x^2\delta^2\cos\theta^2 \\ &= L^2 - 2Lx\delta\cos\theta + x^2\delta^2\end{aligned}$$

We may then use this relation to estimate the parameters L, δ, and $\cos\theta$ by a nonlinear least squares method (Gauss-Newton Method).

End manipulator

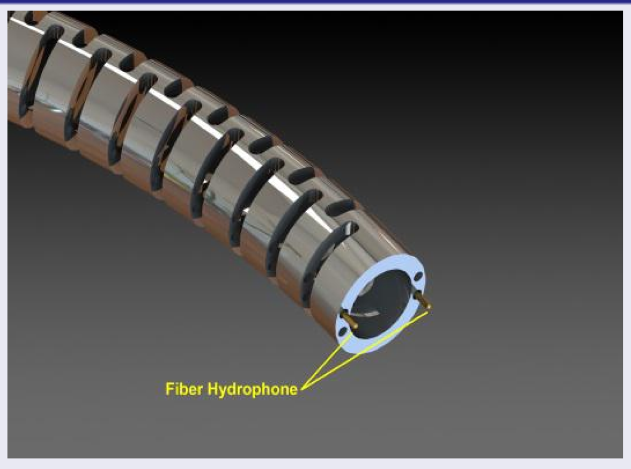
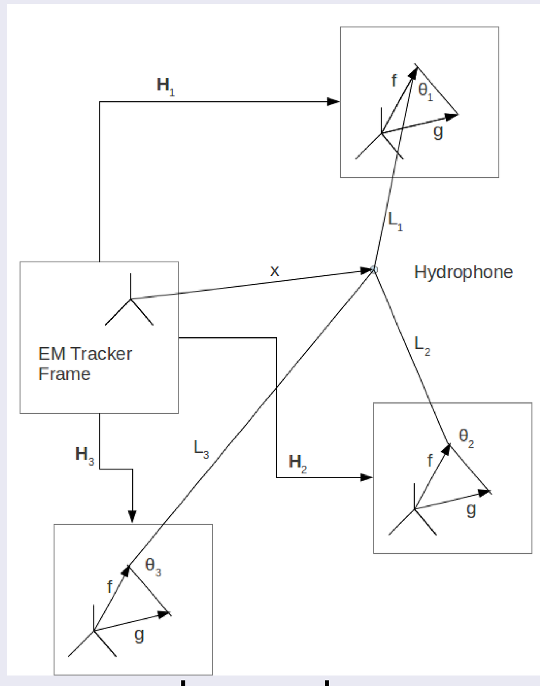


Figure: Courtesy of Xiaoyu Guo

EM-to-Ultrasound Calibration



There is a need to find the location and orientation of the ultrasound array in the ultrasound probe frame. To find this we collect several sets of readings from different configurations and preprocess them.

There are two equations for each reading ($j \in [1..n]$):

$$\|H_j\vec{f}\| = L_j^2$$
$$(H_j\vec{g} - H_j\vec{j}) \bullet (H_j\vec{f}) = L_j \cos\theta_j$$

Derivation not shown, but we can reduce the problem to solving a system of linear equations in six unknowns the two equations below added for each reading (we therefore need at least three readings to calibrate):

$$2(\vec{t}_{(j)} - \vec{t}_{(j+1)})^T\vec{f} = L_{(j)}^2 - L_{(j+1)}^2 + \|\vec{t}_{(j+1)i}\| - \|\vec{t}_{(j)i}\|$$
$$(\vec{t}_{(j)} - \vec{t}_{(j+1)})^T(\vec{g} - \vec{f}) = L_{(j)}\cos\theta_{(j)} - L_{(j+1)}\cos\theta_{(j+1)}$$

where,

$$H\vec{v} = R(\vec{v} + \vec{t})$$

Results

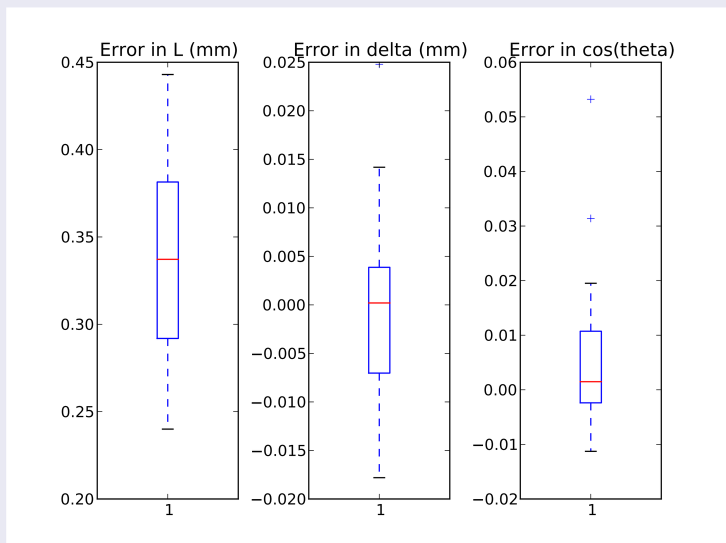


Figure: Single reading errors.

A simulation of one hundred readings was conducted with a parameters and noises expected of our system.

EM-to-US calibration is performed in a water tank prior to the procedure. There is a need to find the location of the hydrophone by pivot calibration using an EM pointer, but this introduces error due to inaccurate hydrophone position. One thousand calibrations were simulated to find the relationship between hydrophone error and calibration error. One hundred calibrations were then performed without any hydrophone position error to find the best case distribution.

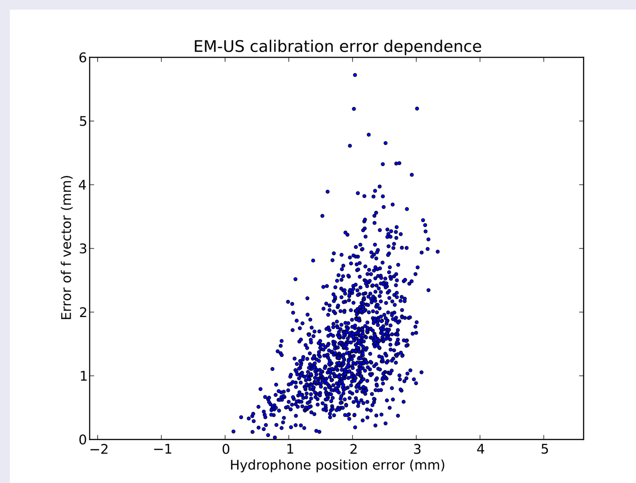


Figure: Error dependence for EM to US calibration.

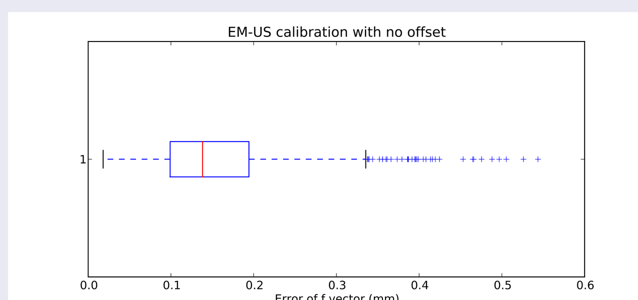


Figure: Calibration error without hydrophone position error.

Future

We were unable to complete the project, so there are still several components left to be completed. We were able to get accurate timing for ultrasound synchronization, but were unable to get reliable readings from the hydrophone. Work is also required to account for different average speed of sound along each path due to changes in bone and tissue geometry. However, this may be performed in the preprocessing step, leaving the calibration method unchanged.

References

Kutzer, Michael DM, et al. "Design of a new cable-driven manipulator with a large open lumen: Preliminary applications in the minimally-invasive removal of osteolysis." Robotics and Automation (ICRA), 2011 IEEE International Conference on. IEEE, 2011.