Needle Tumor Puncture Detection Using Force and Position Time Series Data

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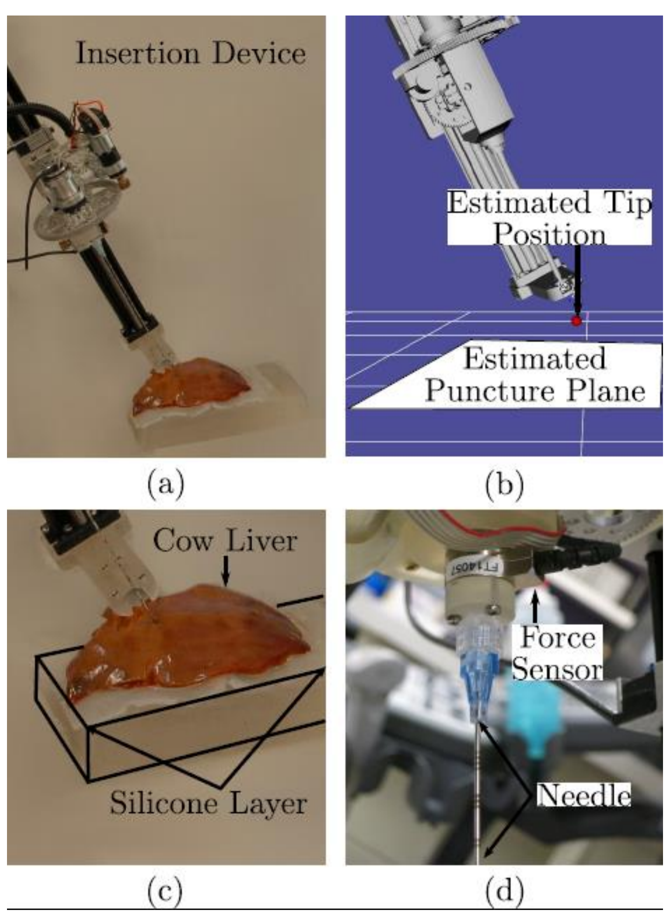
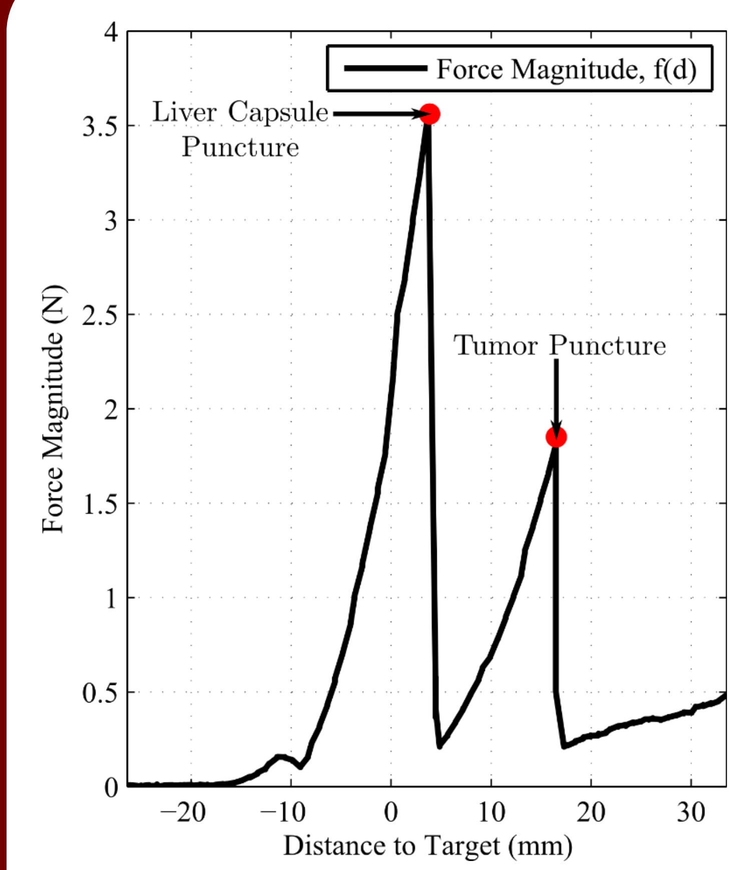
Introduction



Many medical applications, such as tumor ablation and spinal tap procedures, require that a surgeon use their sense of touch to identify if a needle has penetrated a barrier and entered a target region. This study uses machine learning to create a classifier that identifies when a needle, instrumented with a force sensor, has punctured a target. This could enable increased precision in surgery or better robotic needle insertion.

Data



- A needle instrumented with a force sensor and tracker was inserted at a constant velocity
- Training data was generated by inserting the needle into two layers of gel surrounding a silicone membrane
- Test set data was collected by inserting the needle into a cow liver placed on top of a silicone layer
- Puncture detection had to generalize to new types of tissue

Force Time Series Features

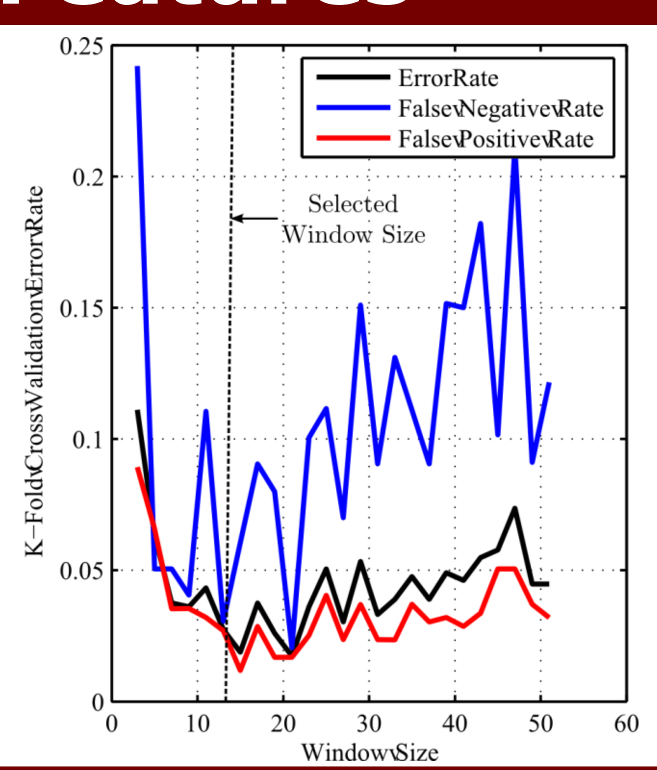
Window of normalized force values used for puncture detection

$$\left(\vec{f}(t-W), \ldots, \vec{f}(t+W)\right)$$

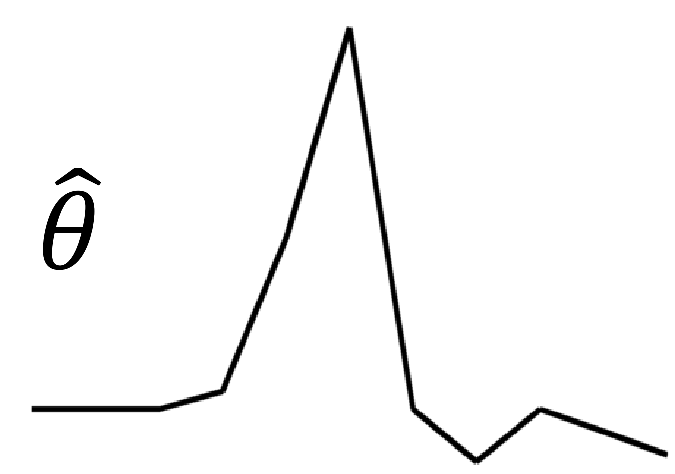
Quadratic features formed from this window

$$\phi(\vec{f}(t-W), \ldots) = \begin{pmatrix} \vec{f}(t-W), \ldots, \vec{f}(t+W), \ldots \\ , \ldots \vec{f}(t-i)\vec{f}(t-j), \ldots \end{pmatrix}$$

$W = 5$ found to be optimal window size from K-fold cross validation



Learned Puncture Shape

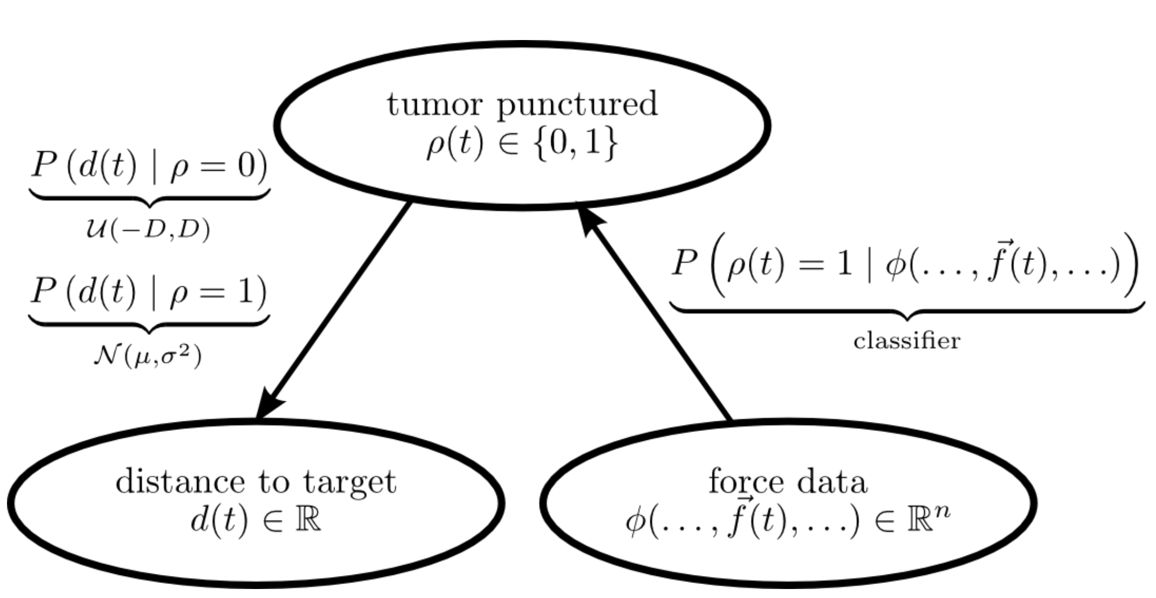


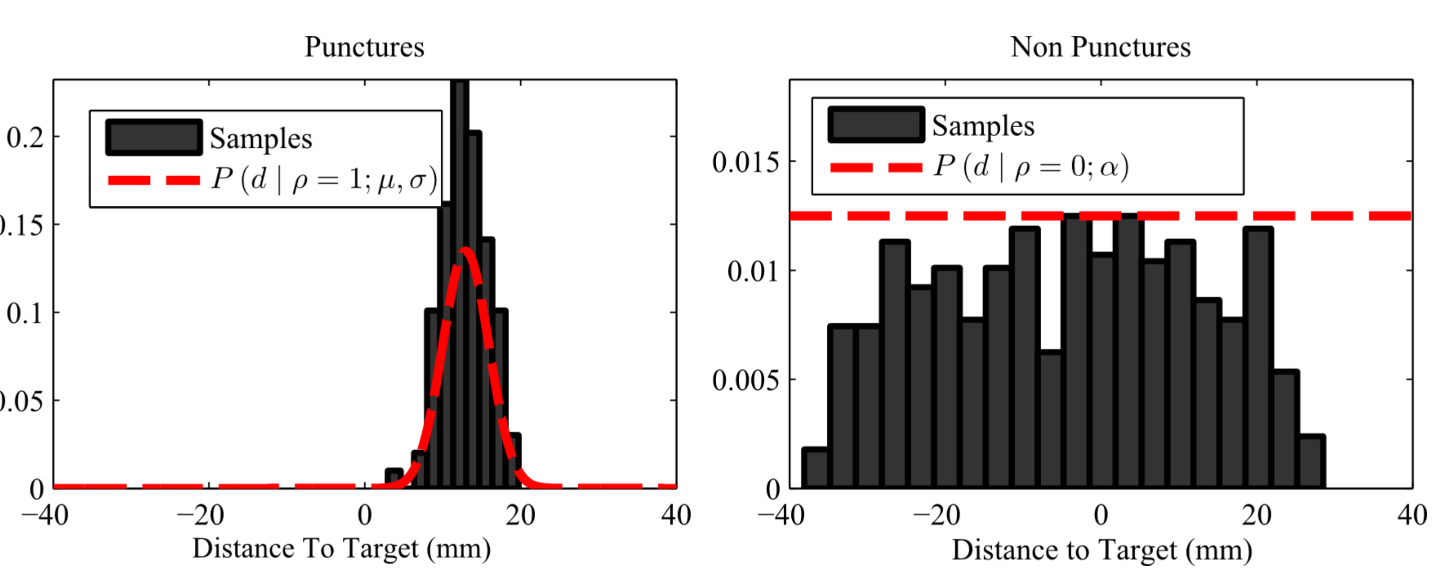
$$\hat{\theta} = \underset{\theta}{\operatorname{argmax}} \prod_{i=1}^{M} p\left(\rho(t)^{(i)} \mid \phi(\vec{f}(t)^{(i)}); \theta\right)$$

$$P\left(\rho(t) \mid \phi\left(\vec{f}(t)\right)\right) = g\left(\hat{\theta}^T \phi\left(\vec{f}(t)\right)\right)$$

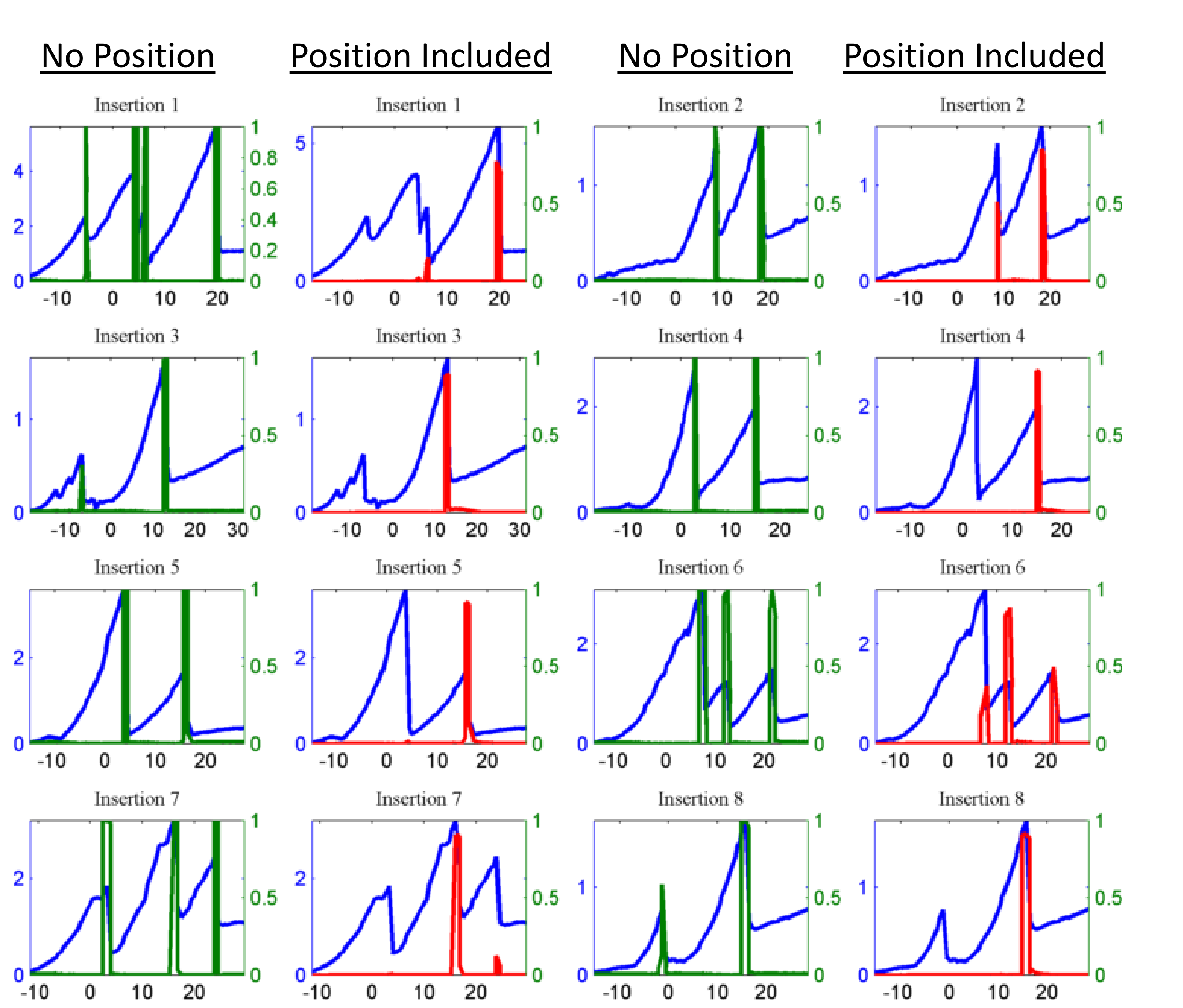
$P(\rho = 1 \mid f)$ maximized when f "looks" like (linear coordinates of) $\hat{\theta}$.

Including Position





Validation on Liver Data



Conclusions

A regularized logistic regression classifier was developed that identifies needle puncture events based on force information alone. This classifier, though trained using a gelatin tissue phantom, generalized well to cow liver. Further incorporation of distance information enabled the algorithm to distinguish between a puncture event that occurred based on interference in the liver from puncture of the target. This work may enable puncture detection for autonomous needle insertion, or give surgeons a new tool to more confidently identify needle puncture in procedures such as tumor ablation.