

## Unexploded Ordnances (UXOs)

Unexploded ordnances (UXOs) consist of munitions such as rockets, artillery shells, and missiles. They are buried in unknown locations and present a danger to civilians because of their explosive nature and their environmental impact. These UXOs can be found in over 23,000 square miles in the US alone. This area encompasses nearly 2,300 sites which are mainly composed of troop training areas, weapons testing sites, and munitions storage facilities. One such site is pictured to the right. CNN featured this Orlando neighborhood in an article because UXOs were found in and around neighborhood schools.



The US alone spent over \$250 million last year in cleaning up UXOs, and it is estimated that the final cost of clearing all of the US's contaminated lands will be approximately \$25 billion.

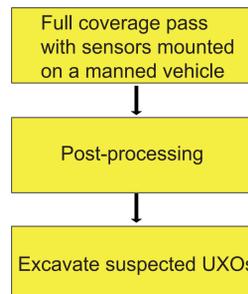


The **goal of this research** is to design a method that will build on current detection strategies. This Bayesian filter based strategy will intelligently place a sensor or a set of sensors in locations that will allow us to more accurately, more robustly, and more efficiently locate and ultimately eliminate UXOs.

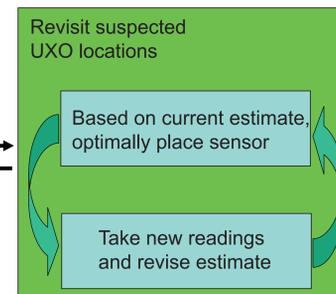
## Search Strategy

The current industry approach to detecting UXOs is to begin with a full coverage sweep of the area. With the help of GPS, a complete coverage of the area is guaranteed and each sensor measurement is geo-tagged. Now, all this data is post-processed and the suspected UXO locations are dug up. Our addition will take the suspected target list and investigate them further with an adaptive sensing approach. With the new information, the post-processing algorithms can be reapplied to generate a new target list.

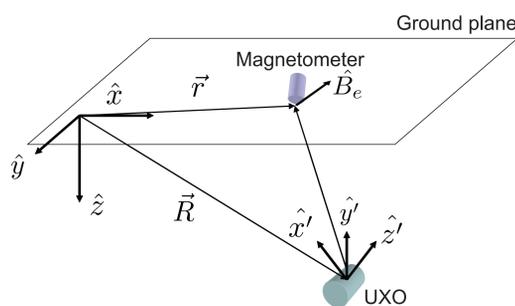
Current Industry Approach



Proposed Addition



## Magnetometer



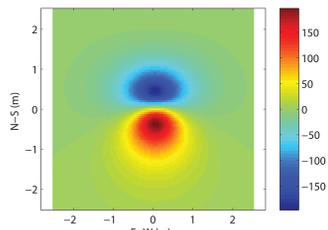
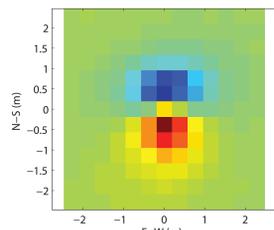
$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi} (3[\vec{m} \cdot (\vec{r} - \vec{R})] \frac{\vec{r} - \vec{R}}{\|\vec{r} - \vec{R}\|^3} - \frac{\vec{m}}{\|\vec{r} - \vec{R}\|^3})$$

$\vec{B}(\vec{r})$  - Magnetic field  
 $\vec{m}$  - Magnetic dipole  
 $\vec{R}$  - Sensor position  
 $\vec{r}$  - UXO position

The above equation represents the magnetic field produced by a magnetic dipole. This is used in industry as a simple model of the magnetic signature created by an UXO. The magnetometer will sense the component of the magnetic field that is normal to Earth's magnetic field,  $\hat{B}_e$ .

$$z = \hat{B}_e \cdot \vec{B}(\vec{r})$$

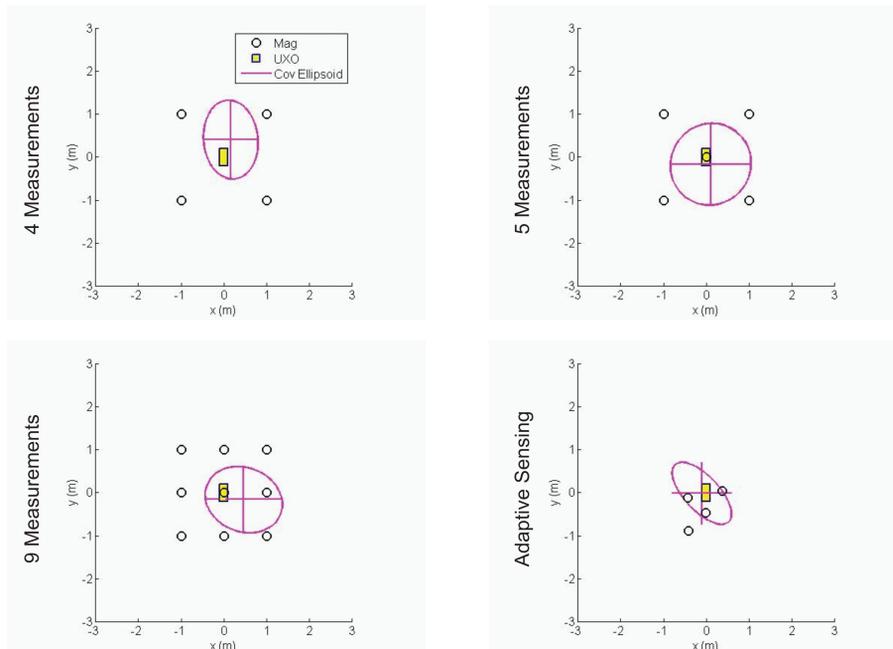
We were able to take some data to validate this model. The max error between the simulated data and actual sensor data was 26.7 nT and the rms error was 6.5 nT. The range of readings was 300 nT.



## Results

Simulations were run to compare the adaptive sensing algorithm with some deterministic approaches. These simulations consider all six degrees of freedom for the UXO parameters, three states for location and three states for the dipole. The deterministic approaches assume a sensor travels in a set pattern centered around a suspected UXO location using four, five, and nine measurements. The adaptive sensing approach uses four consecutive measurements basing each new sensor position on the current best UXO estimate.

Plotted below are the top down views of the simulations after the trajectories were complete. They show all the sensor locations, the actual UXO location, and the estimated UXO location and uncertainty. The adaptive sensing method shows similar accuracy, but much reduced uncertainty when compared to the deterministic approaches with more sensor readings. The reduced uncertainty corresponds directly with an increase of information about the UXO. The table below shows the results from running these simulations 200 times.

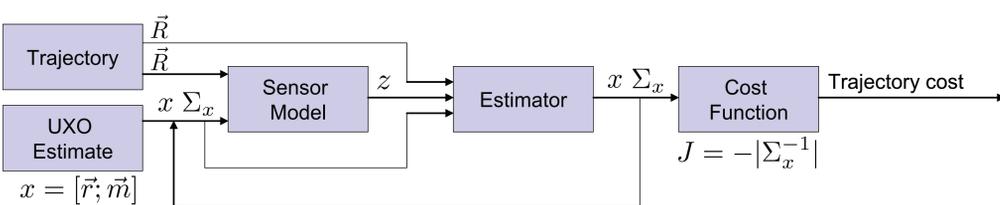
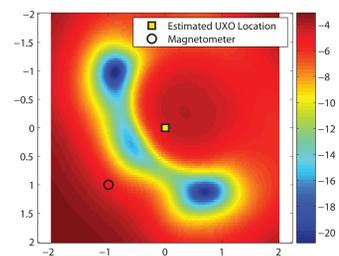


Trajectory	4 Mzs	5 Mzs	9 Mzs	A.S.
$\ \vec{R} - \vec{R}_{act}\ _2$ [m]	0.32	0.36	0.40	0.11
$ \Sigma_{\vec{R}} $ [m <sup>2</sup> ]	8.5e-3	5.8e-3	0.7e-3	0.1e-3

## Adaptive Sensing

This method tries to maximize the amount of information obtained by the sensors. The block diagram at the bottom describes how a cost is determined that represents the estimated information generated by a trajectory. Each trajectory describes a feasible path for a sensor. In this situation, the magnetometer is used. The estimator chosen is the sigma-point Kalman filter. It is a nonlinear filter that produces a state estimate of the UXO parameters and an uncertainty. The optimal trajectory will be the trajectory with the minimum associated cost.

On the right is a sample cost map generated with trajectory consisting of two time steps. The first sensor location is shown on the plot. The optimal location to take the next sensor reading is along the blue sections of the cost map.



## Conclusion

We have developed an algorithm that builds on current UXO detection strategies. This technique attempts to maximize the amount of information a sensor will collect about a specific target for each measurement. The sensor presented here is the magnetometer. Future research will extend this algorithm to use other common UXO sensors such as electromagnetic induction sensors and ground penetrating radars.

Because of the nature of the cost function, this algorithm can easily be extended to incorporate multiple sensors as long as good equation models exist. Some possible future applications include: autonomous rescue beacon locator, mine clearance, and autonomous docking.

## Acknowledgements

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## References

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