Dry coupled magnetostrictive transducers for robotic inspection of dry storage casks

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Background

The lack of a national repository for used nuclear fuel has lead to the usage of dry storage casks as the de facto long term storage solution, the usage of which is prevalent throughout the United States (figure 2). Furthermore, as shown in figure 3, the usage of dry storage is only expected to increase over time. Because these casks were originally intended as only an interim measure, there is an urgent need to develop methods to monitor their structural health over the long-term. Additionally, when concerns about the susceptibility of these casks to cracking is considered, the need for inspection becomes even more apparent [1].

Figure 1: Connecticut Yankee dry storage site [2]

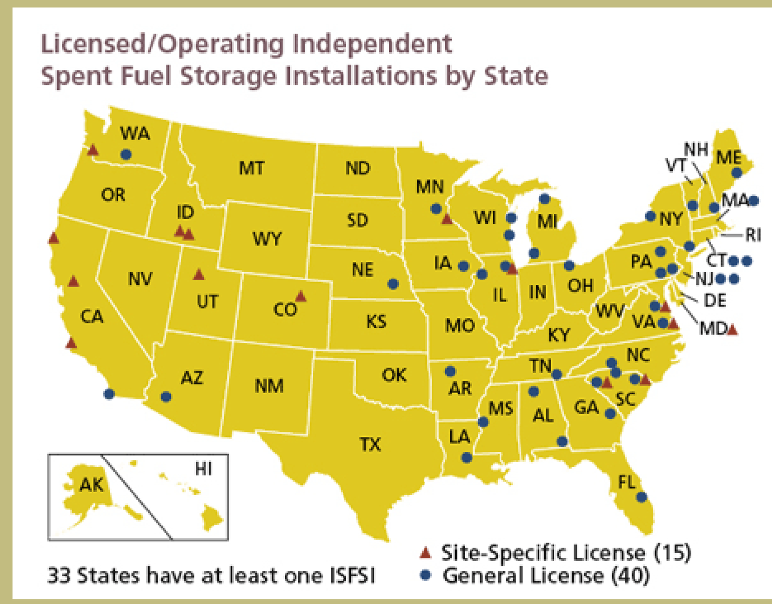

Figure 2: Used fuel storage sites in the United States [3]

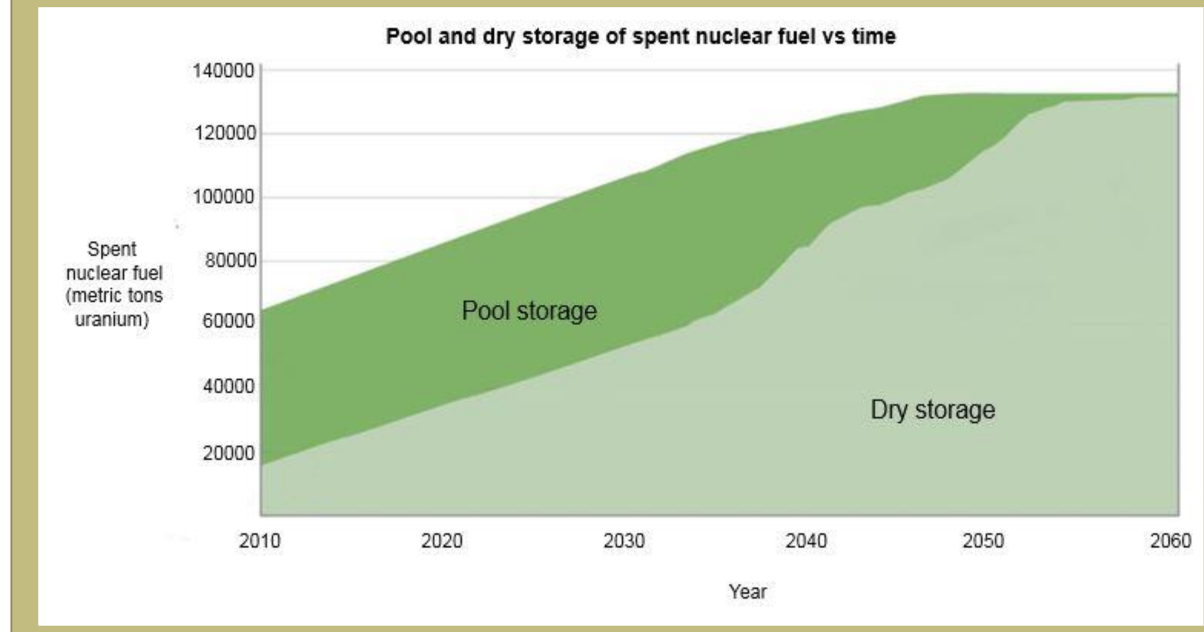

Figure 3: Projected increase of dry storage over time [4]

The use of robotic devices to inspect the interior of these casks for signs of damage has been proposed [5], but in order for this to be realized, advances in sensing technology must occur. We develop a novel type of transducer for non-destructive evaluation to aid in these efforts. We construct a prototype sensor, demonstrate simple defect detection with it, and present a design for an inspection robot equipping these transducers.

Principles of operation

Ultrasonic inspection is a well known method of non-destructive evaluation which works by measuring the response of ultrasonic waves propagating through a material. In through-transmission inspection, a transmitter and receiver are used to generate and detect waves in the material to be inspected. The presence of a crack or defect in the material will scatter some of the transmitted wave's energy, reducing the strength of the response at the receiver (figure 4).

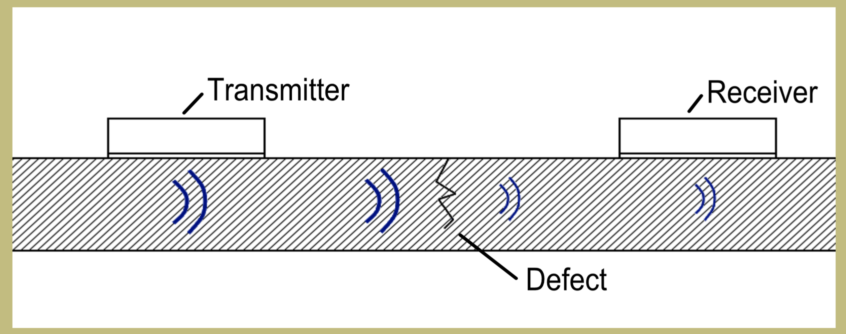

Figure 4: Illustration of through-transmission ultrasonic inspection

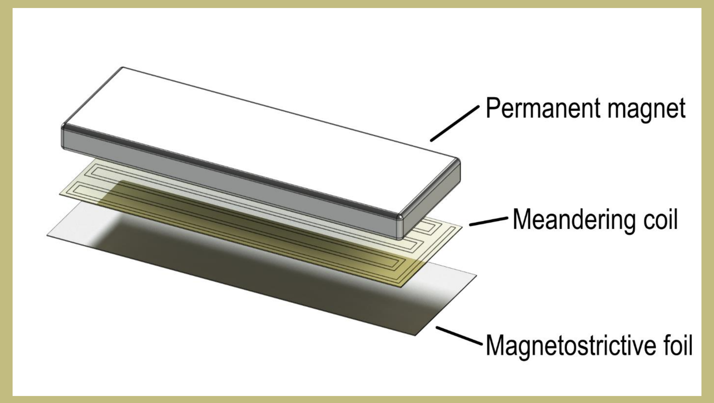

Figure 5: Components of a magnetostrictive transducer

Magnetostrictive transducers are often used to generate and detect guided waves. These transducers depend on the magnetostrictive effect, where certain materials will deform in the presence of a magnetic field. The typical construction of one of these transducers is shown in figure 5, consisting of a magnetostrictive foil, meandering coil, and a biasing magnet. Materials typically used for the foil include Fe-Co and Terfenol-D. For wave generation, a high-frequency alternating current is supplied to the coil of the transducer, which generates an oscillating magnetic field that causes the foil to deform. For reception, the inverse occurs: deformation of the foil results in a current in the coil that can be detected. The deformation of the foil is usually coupled to the material to be inspected with an adhesive, and waves are transmitted through this bond. Obviously, an inspection robot cannot have its sensors bound to the surface of the cask.

Prototype construction and testing

Using the basic transducer design in figure 5, we experimented with various configurations of materials and geometry. In order to gather relevant data, we used force sensitive resistors to measure applied force, and a Matec computer system to generate and measure ultrasonic waves. A testing rig was constructed to simulate the geometrical constraints of the interior of the cask (figure 6), and we experimented using deadweights, a pneumatic cylinder, and an air bladder (shown) to apply the force.

It was discovered early in the testing process that the performance of the transducer was very sensitive to the alignment of the components, and the method by which the foil was attached. To maximize performance, we designed an enclosure that would hold the components in alignment while still allowing the foil to float (figure 7).

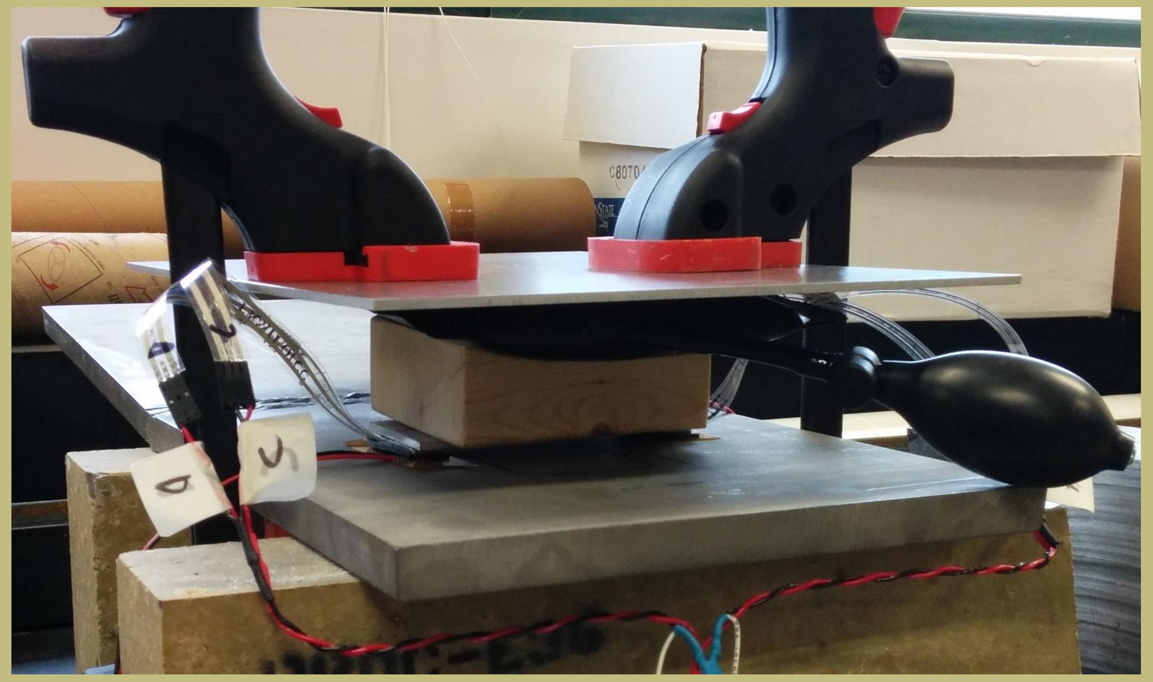

Figure 6: Testing rig

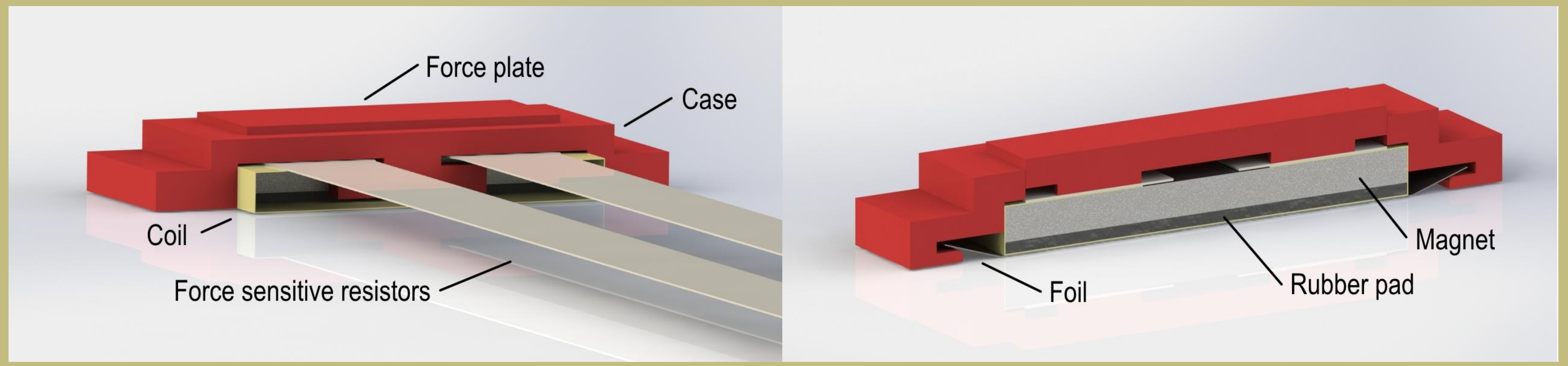

Figure 7: The prototype transducer

Testing and results

To test the effectiveness of our new transducer, we cut circular holes of varying diameter in 2mm aluminum plate, and measured the response across them. The data from this experiment can be seen in figure 8.

It can be seen that there is a clear relationship between the strength of the received signal and the force applied, and to a lesser extent, the size of the defect. This design performs adequately as a proof of concept, and a more precisely fabricated enclosure should further increase the accuracy of its measurements.

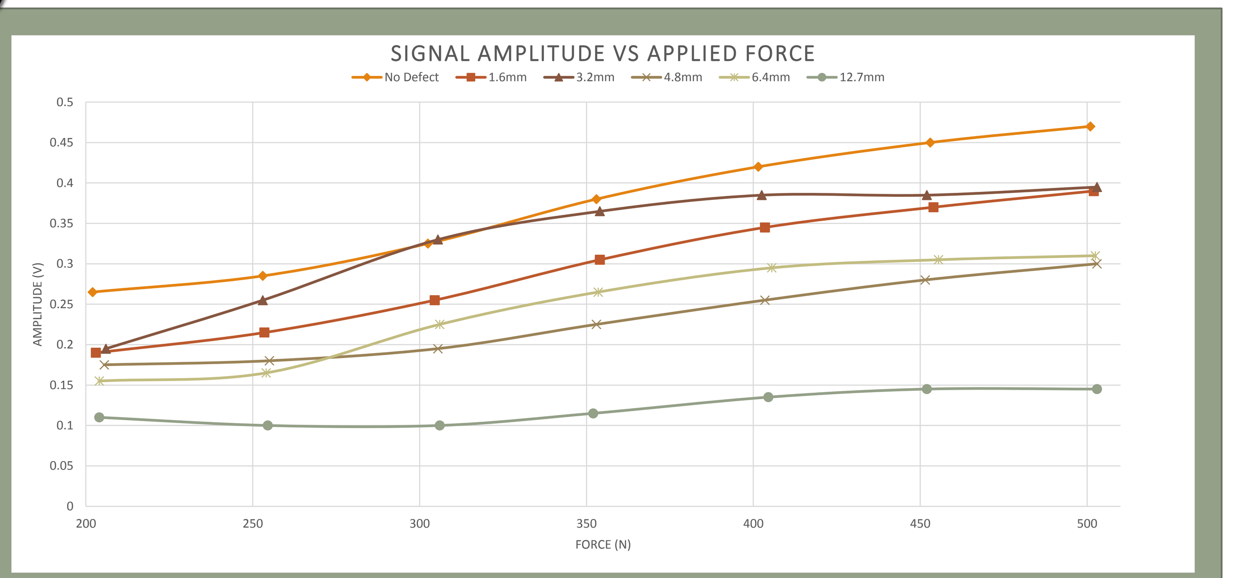

Figure 8: Response of the prototype to various defects. Data points are median values over 4 runs.

Robot design

A robot is being designed for inspection, and it must deal with many challenges inside the cask, including tight confines, right-angle transitions, high temperatures, and radiation. A schematic of a representative storage cask is shown in figure 9, where the narrow ventilation channel between the MPC and overpack can be seen.

For our initial design, we consider only the geometrical constraints, and in figure 10, present a design for a prototype that can be assembled from COTS components. The robot needs to be articulated to navigate the bends in the cask, so each wheel is individually actuated. The robot is controlled via a tether, which also supplies electrical power and compressed air. For localization, ultrasonic rangefinders and a camera are equipped.

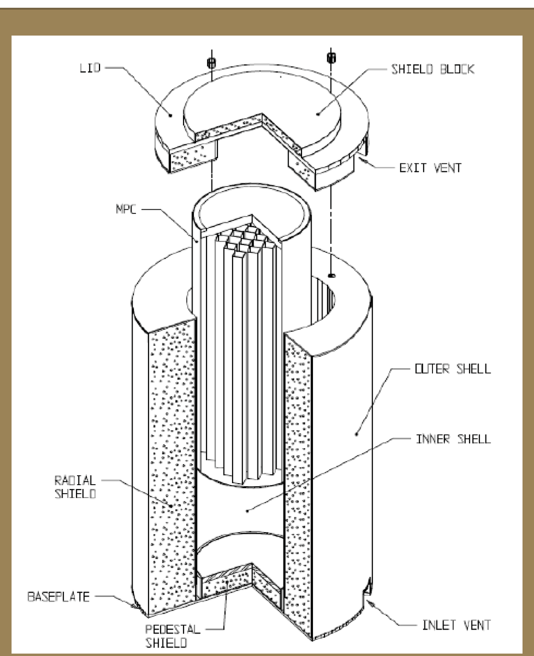

Figure 9: Schematic of a dry storage cask [1]

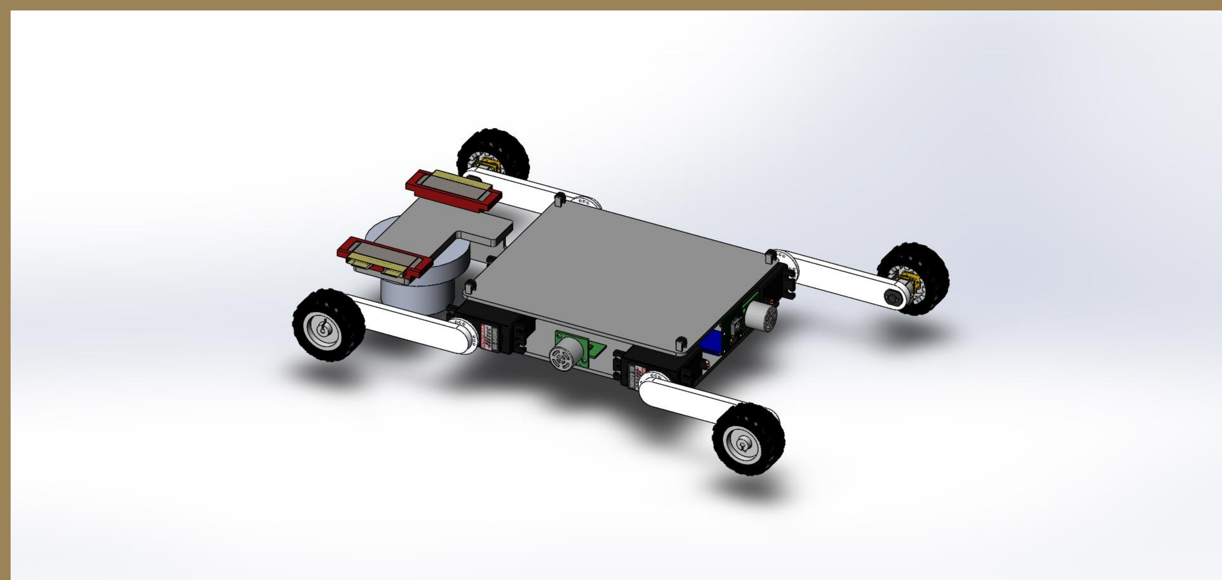

Figure 10: Proposed inspection robot prototype

References

[1] R. Meyer *et al.*, "NDE to Manage Atmospheric SCC in Canisters for Dry Storage of Spent Fuel: An Assessment", PNNL, 2013.
[2] Connecticut Yankee, "Fuel Storage and Removal", http://www.connyankee.com/html/fuel_storage.html, accessed 2015-02-19.
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[4] BRC, "Blue Ribbon Commission on America's Nuclear Future", 2012.
[5] C. Lissenden *et al.*, "Multi-Sensor Inspection and Robotic Systems for Dry Storage Casks", 2014.

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