INSPIRE

INSPECTING AND PRESERVING INFRASTRUCTURE THROUGH ROBOTIC EXPLORATION

UAV Enabled Measurement for Spatial Magnetic Field of Smart Rocks in Bridge Scour Monitoring

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Outline of This Presentation

- Introduction
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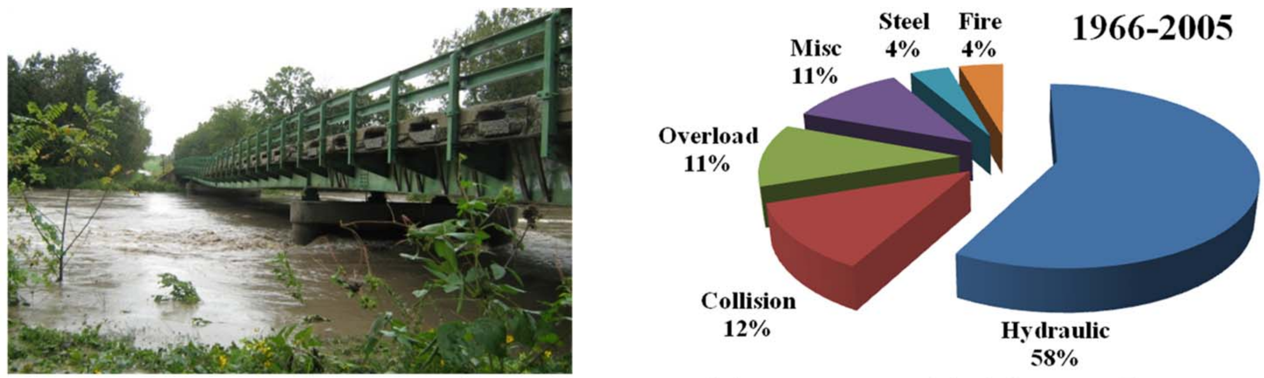
  - Scour mechanism and monitoring techniques
- Concept of Smart Rocks
  - The smart rock technology and applications
  - Proof-of-concept testing
- System Integration
  - Magnetometer and GPS installed on a UAV
  - Motor effect on magnetic field measurement
- Field Studies
  - Magnetic field interference of two smart rocks
  - "Crane" vs UAV based measurement accuracy
- Concluding Remarks

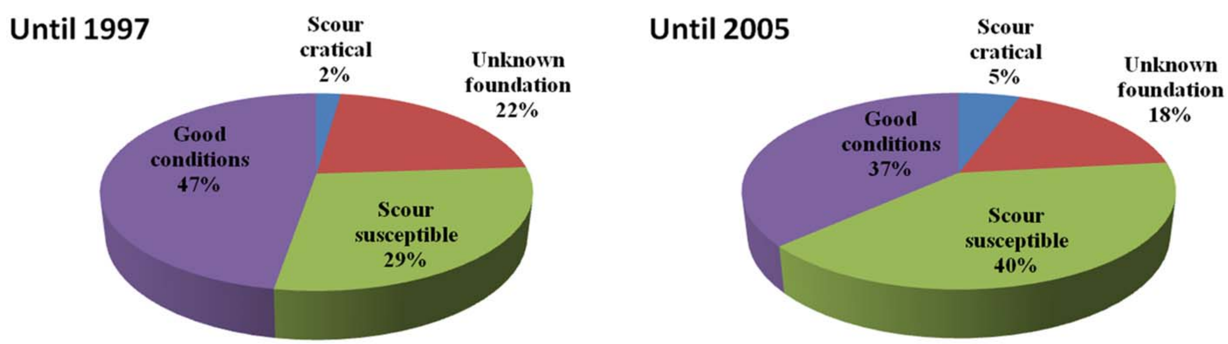
Introduction

- **Needs for Bridge Scour Monitoring**



(a) Loss of center pier (b) Causes of bridge collapse

Scour-induced bridge damage and statistics

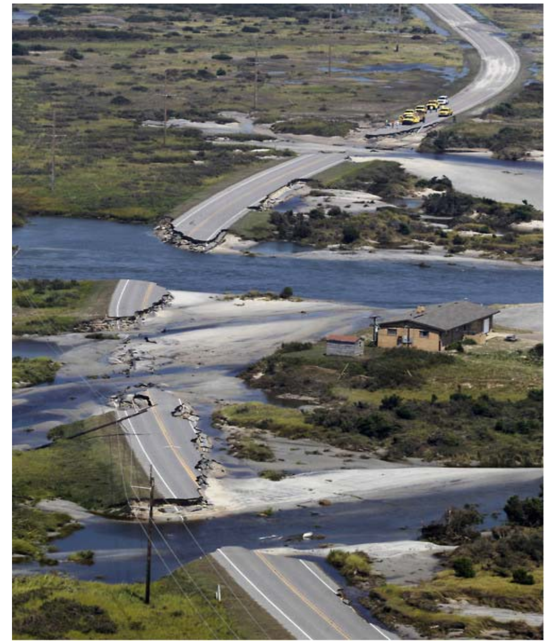


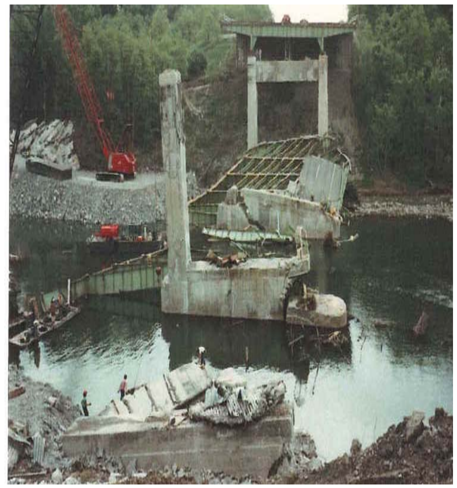
(a) Prior to 1997 (b) Prior to 2005

Growing problems with bridge scour

Introduction

- Disruption to Service

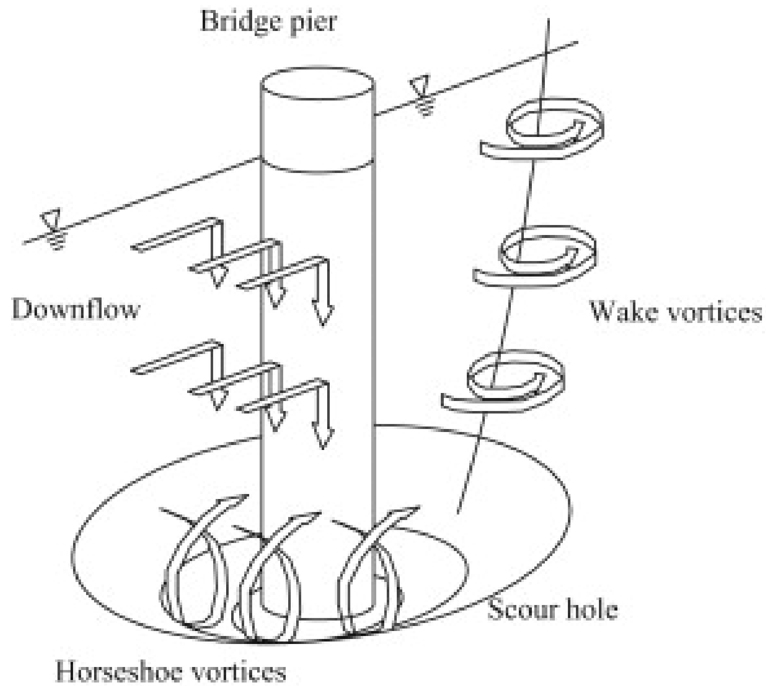




- Threat to Safety
- Cost to Scour Mitigation

Introduction

- **Scour Mechanism**
  - **An engineering term for the erosion of riverbed deposits caused by complex water flow around a bridge foundation (piers and abutments)**



L.J. Prendergast, K. Gavin. A review of bridge scour monitoring techniques. Journal of Rock Mechanics and Geotechnical Engineering. 2014; 6. 138~149

Introduction

- **Existing Scour Monitoring Methods**
  - **Fixed instrumentation**
    - ✓ ***Magnetic sliding collar***
    - ✓ ***Tilt sensor***
    - ✓ ***Float-out device***
    - ✓ ***Time domain reflectometry***
    - ✓ ***Fiber optic sensor***
    - ✓ ***Piezoelectric film sensor***
    - ✓ ***Temperature sensor***
    - ✓ ***Vibration based methods***
    - ✓ ***Smart scour sensor***
    - ✓ ***Medium property sensor***
  - **Portable instrumentation**
    - ✓ ***Radar***
    - ✓ ***Sonar***
    - ✓ ***Sounding rods***
    - ✓ ***Radio-Controlled Boat***
    - ✓ ***Tracking or imaging sensor***

Questions:

- How critical of the measured information when the initiation of a scour hole is unknown?
- How rugged to operate in harsh environment?

Problem:

- Too risky to operate during a flood event

Introduction

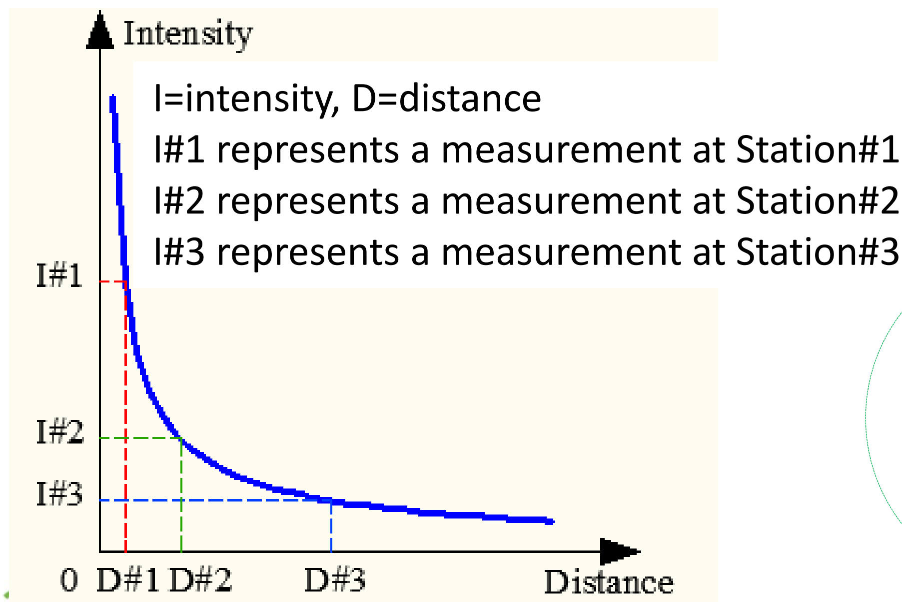
- Objectives
  - To develop a moving unmanned aerial vehicle (UAV) platform for rapid measurement of magnetic field,
  - To characterize the movement of smart rocks deployed at the riverbed near a bridge pier based on the air-borne measurement difference of magnetic fields before and after deployment of the smart rocks, and
  - To evaluate the field performance of the smart rocks for real time monitoring of bridge scour during significant flood events.

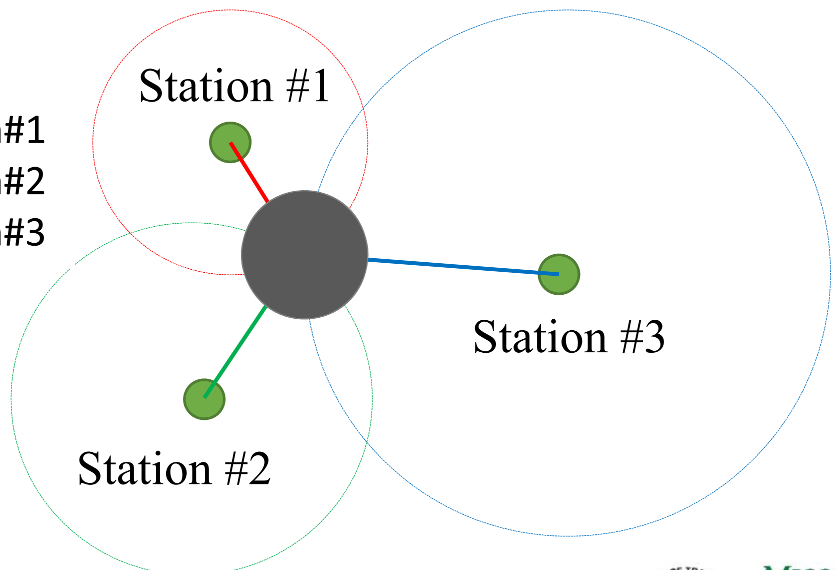
Introduction

- The Scope of Work in Years 1 and 2 is
  - To design, build, and test a UAV with no more than 90-N payload of a 3-axis magnetometer, a lightweight onboard computer, and one or two batteries for at least 20 minute operation in field condition,
  - To establish the relation between the flight speed and the sampling rate of the magnetometer,
  - To evaluate the localization accuracy of one, two, and three smart rocks.
  - To develop a ground-referenced GPS on a UAV to accurately measure its coordinates,
  - To investigate the potential effect of UAV rotations on magnetic field measurements, and
  - To demonstrate the field performance of smart rocks with a UAV-supported 3-axis magnetometer at bridge sites.

Concept of Smart Rocks

- **The Technology**
  - **A magnet is embedded in a concrete encasement or a natural rock.**
  - **The magnetic field intensity of the magnet is measured with a magnetometer at distance.**
  - **The intensity measurements at three or more stations allow the determination of the magnet's location.**





Concept of Smart Rocks

- **Application Scenarios**
  - **Maximum Scour Depth around a pier or abutment for design and retrofit. A smart rock rolls to the bottom of a scour hole when formed with unknown location and depth as deposits around the hole are washed away.**
  - **Rip-rap countermeasure effectiveness. A smart rock is mixed with natural rocks as a rip-rap measure to foundation scour. As it moves, the scour countermeasure begins compromised.**

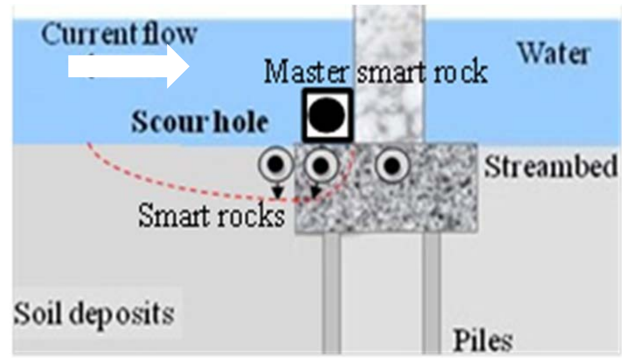


Fig. 1 Maximum Scour Depth Monitoring

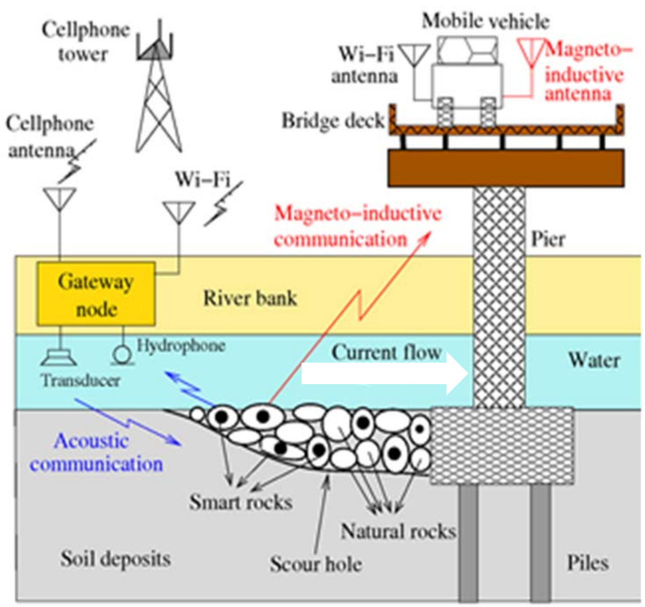
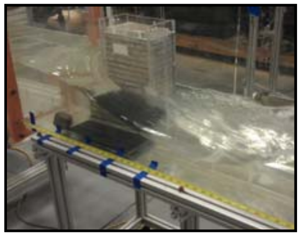
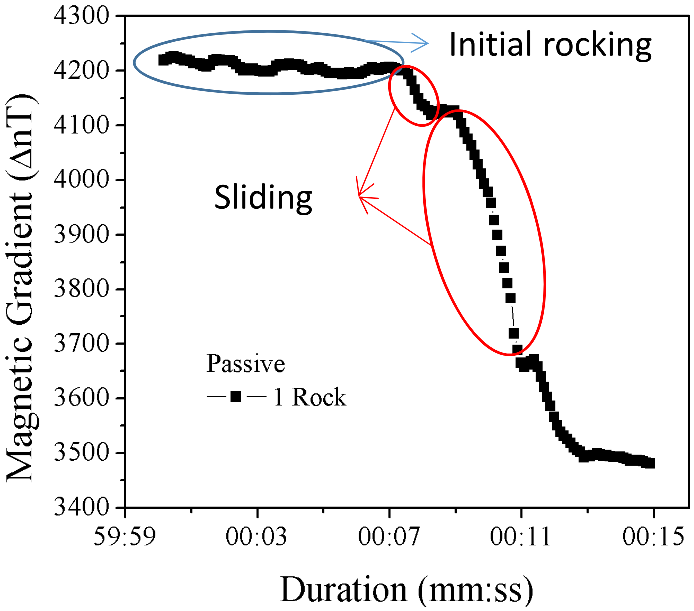


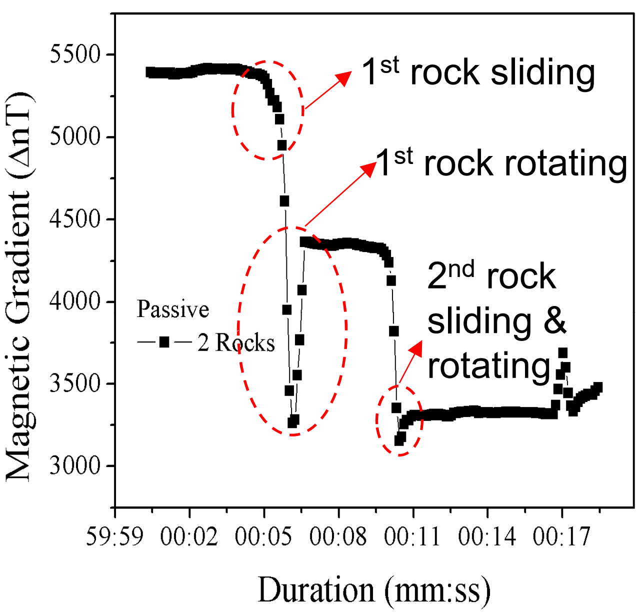
Fig. 2 Scour Countermeasure Monitoring

Concept of Smart Rocks

- **Proof-of-concept Test at TFHRC Hydraulic Engineering Laboratory**
  - **One rock with an embedded small magnet**
  - **Two rocks with embedded small magnets**

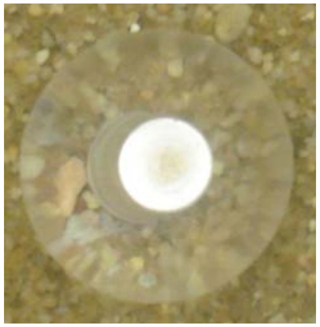






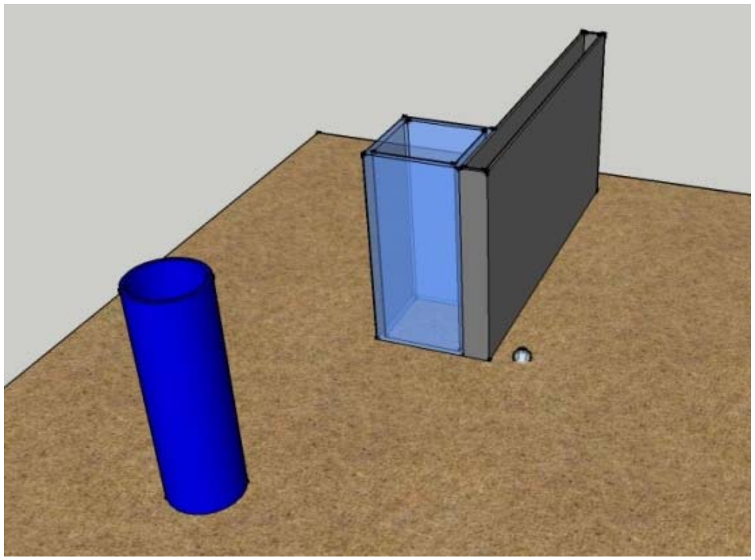
Concept of Smart Rocks

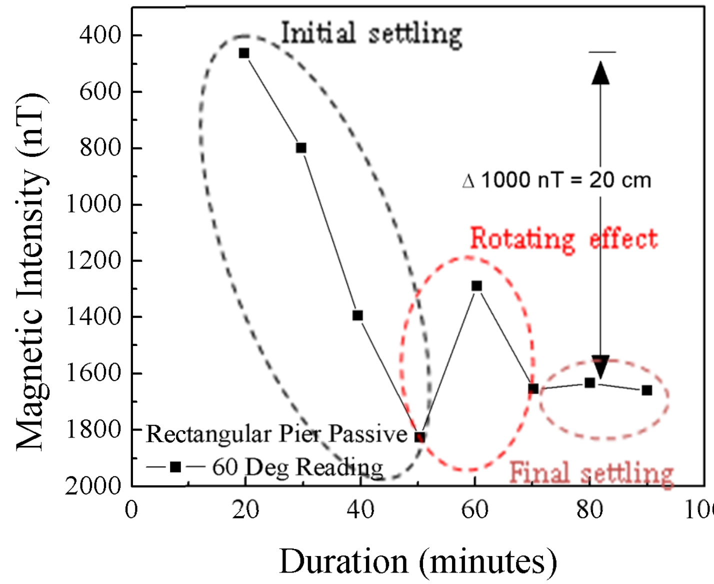
- **Proof-of-concept Test at TFHRC Hydraulic Engineering Laboratory**
  - **7/16” by 1” magnet embedded in a plastic sphere and placed in front of a small-scale pier model**



Concept of Smart Rocks

- **Proof-of-Concept Test with One Rock**

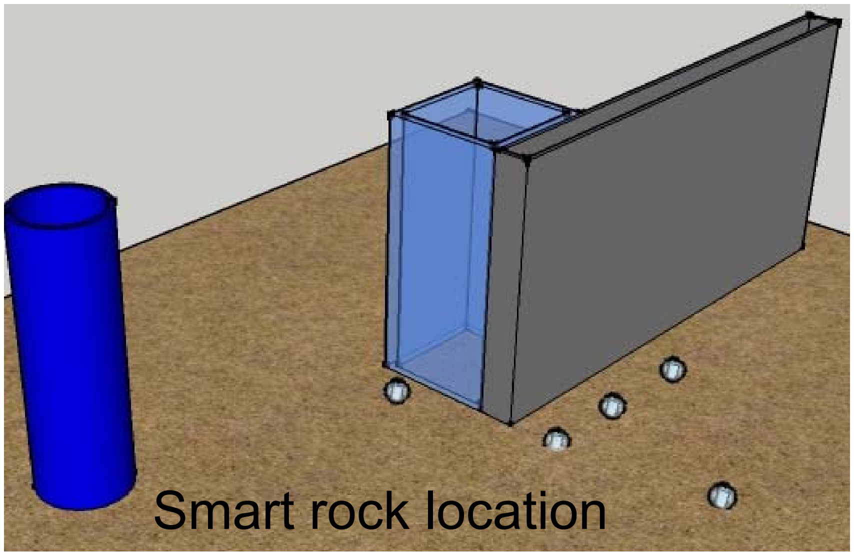


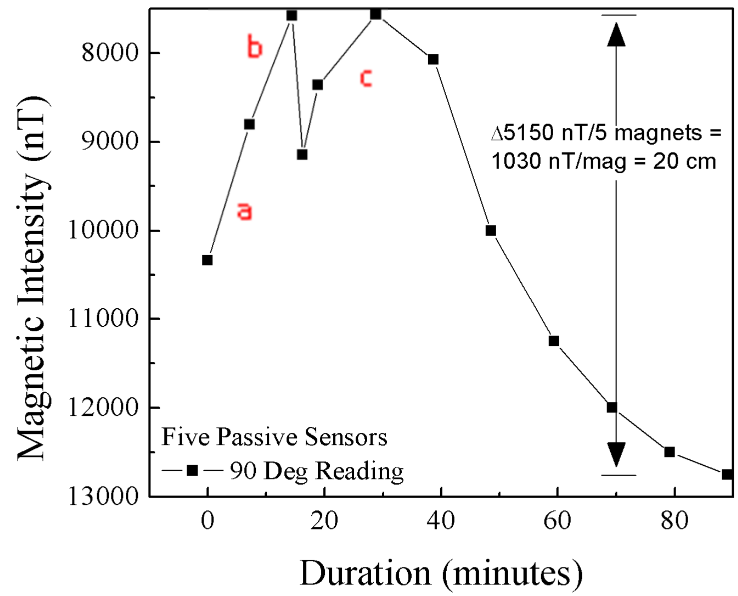


Genda Chen, Brandon Schafer, Zhibin Lin, Ying Huang, Oscar Suaznabar, Jerry Shen, and Kornel Kerenyi. “Maximum Scour Depth Based on Magnetic Field Change of Smart Rocks for Foundation Stability Evaluation of Bridges.” Structural Health Monitoring, 14(1): 86-99, January 2015

Concept of Smart Rocks

- **Proof-of-Concept Test with Five Smart Rocks**





Intensity change over time
with intensity-distance correlation

System Integration

- **Rapid Collection of Dense Data with a UAV**
  - **Can improve the accuracy of smart rock localization and movement prediction at bridge sites.**
- **GPS Integration into the UAV**
  - **A HERE+ GPS module uses a GPS unit at a known ground reference location and another unit on the UAV.**
  - **The ground unit gives a GPS drift error for the location that is currently being used, and relays that drift to the unit on the drone which then calculates a position within a 2 cm bubble.**
  - **The ground reference point can be obtained either by using established USGS markers or measuring the drift in a specific location over time before flying. The self-established position can be reused if the ground unit's location is unchanged during future deployments.**

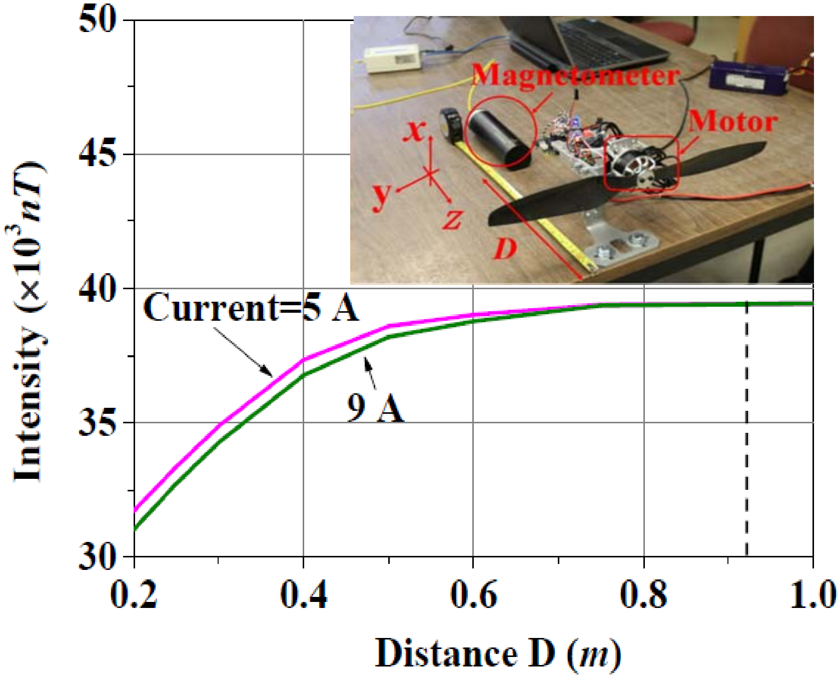
System Integration

- **Magnetometer Integration into the UAV**
  - A 3-axis magnetometer is fixed with two truss members on the UAV. An Ethernet cable is used to connect the magnetometer to a CPU on the UAV.

  - The drone is equipped with multiple compass units to track its heading within 0.2 degrees. If the compasses are in disagreement, the compass health errors will display on the UAV ground station software and a recalibration is required when the UAV stands still.

System Integration

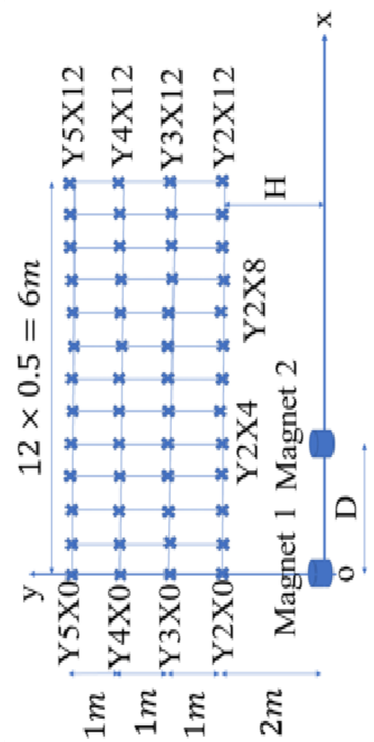
- **Although the UAV used in this study is mainly made of non-ferrous materials, the electric current that drives motors produces an unwanted magnetic field.**

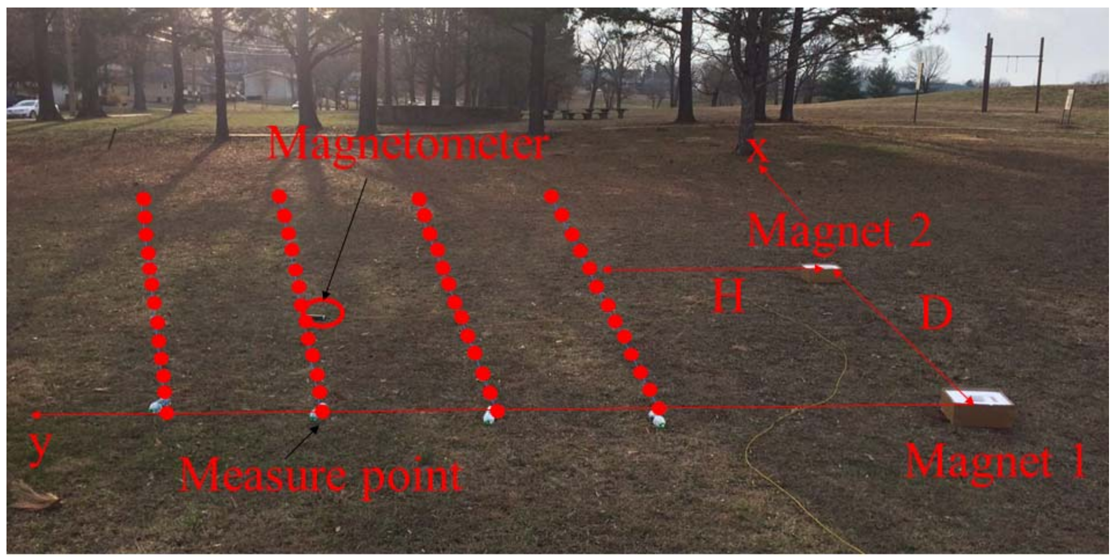


At 0.92 m distance as used in field tests, the motor effect is negligible up to 9 A.

Field Studies

- **Test Plan and Setup to Understand Potential Interference on Magnetic Field of Two Rocks (or Localization of Two Rocks)**



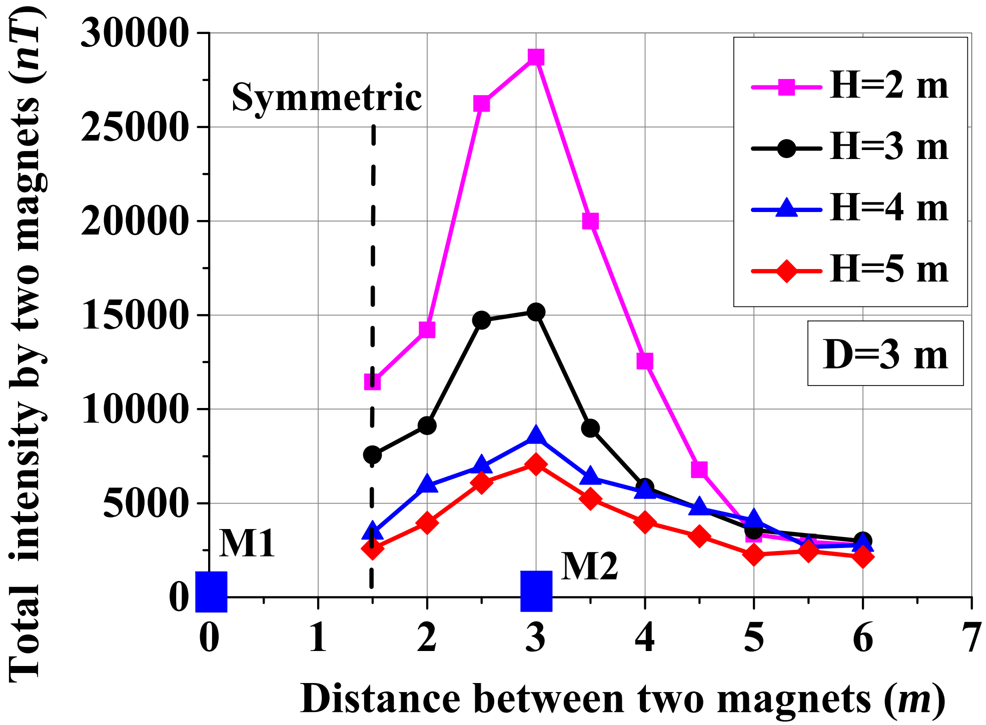


Field Studies

- **Test Procedure to Understand Potential Interference on the Magnetic Field of Two Rocks**
  - Measure the Earth magnetic field at one point when it can be assumed to be constant in a small test area.
  - Deploy Magnet 1 (two stacked N42) at Point (0,0,0) with S direction pointing to y positive axis, and measure the magnetic field at Point (1,0,0), (2,0,0), and (3,0,0).
  - Deploy Magnet 2 (two stacked N42) at Point (2,0,0), (4,0,0) and (6,0,0), respectively, and measure the corresponding magnetic field at Point (1,0,0), (2,0,0), and (3,0,0).
  - Remove Magnet 2, and measure the magnetic intensity at all points.
  - Deploy Magnet 2 at Point (D,0,0) with S direction pointing to y positive axis, and measure the magnetic intensity with D=2m, 3m, 4m, respectively.

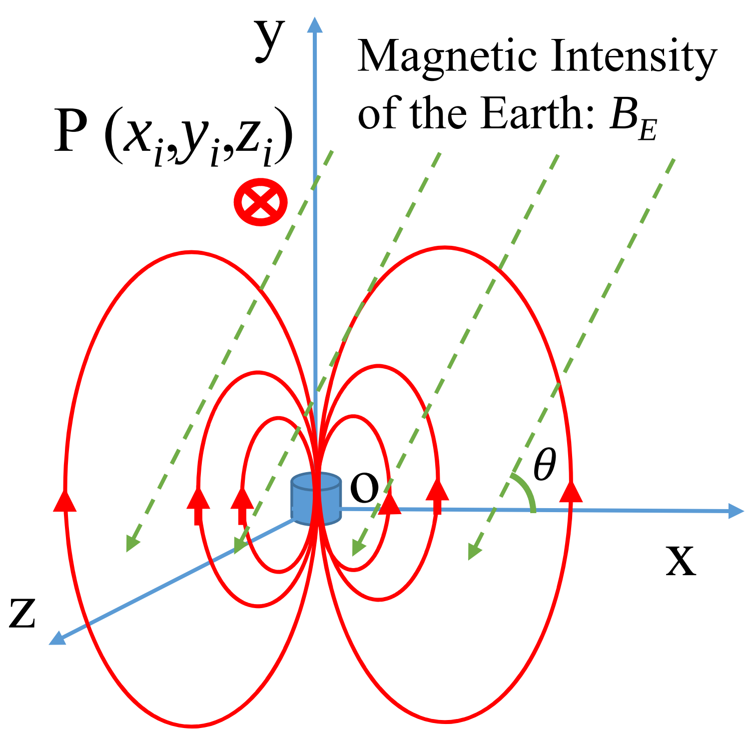
Field Studies

- **Preliminary Test Results**
  - ➢ **Magnetic field interference is negligible when two magnets are placed at 3 m apart.**



Field Studies

- **Localization Algorithm for a Single Magnet**



Magnetic Intensity of a Magnet: B_m

$$\begin{cases} B_{mxi} = k\dfrac{3x_i y_i}{r_i^5} \\ B_{myi} = k\dfrac{2y_i^2 - x_i^2 - z_i^2}{r_i^5} \\ B_{mzi} = k\dfrac{3z_i y_i}{r_i^5} \end{cases}$$

$$r_i = \sqrt{x_i^2 + y_i^2 + z_i^2}$$

k is a constant.

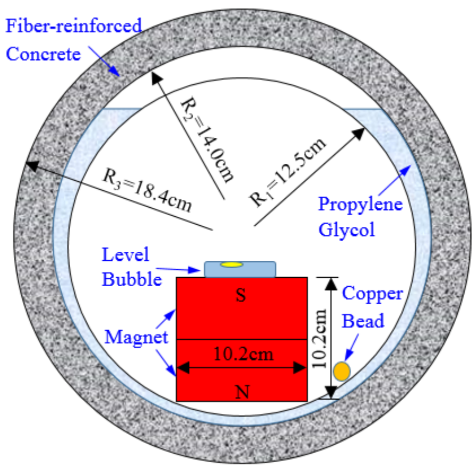
$$B_i^{(P)} = \sqrt{[(B_{mxi} + (-B_e \sin\theta)^2] + [(B_{myi} + (-B_e \cos\theta)^2] + (B_{mzi})^2}$$

B can also be measured with a 3-axis magnetometer. By minimizing the prediction error of the total magnetic field, the rock position can be determined.

$$J(x_i, y_i, z_i) = \sqrt{\sum_{i=1}^{n} [B_i^{(P)} - B_i^{(M)}]^2}$$

Field Studies

- **Smart Rock Design Based on Flow Velocity**
  - ➢ Gravity-controlled magnet polarization direction to minimize the influence of steel rebar in bridge piers
  - ➢ Spherical encasement to make it easy to roll to the bottom of a scour hole



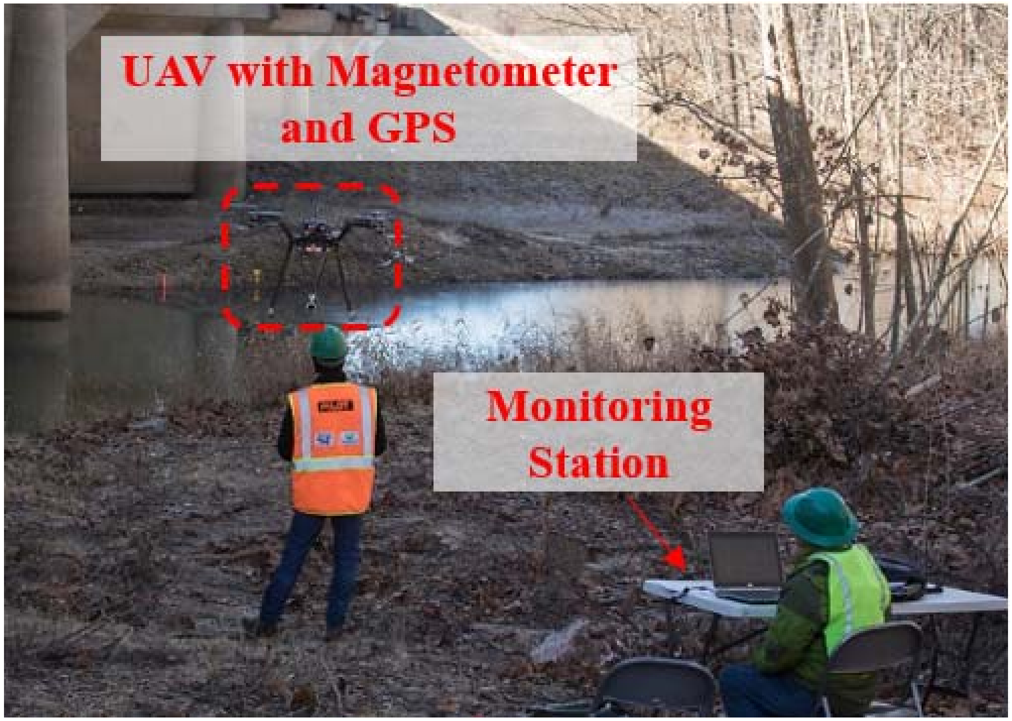
(a) schematic view

(b) Inner structure

(c) Fabricated Smart Rock

Field Studies

- **Smart Rock Deployment and Measurement at Pier 7 of the Roubidoux Creek Bridge (I-44W)**



Field Studies

- **Magnetic Field Measurement with a UAV**

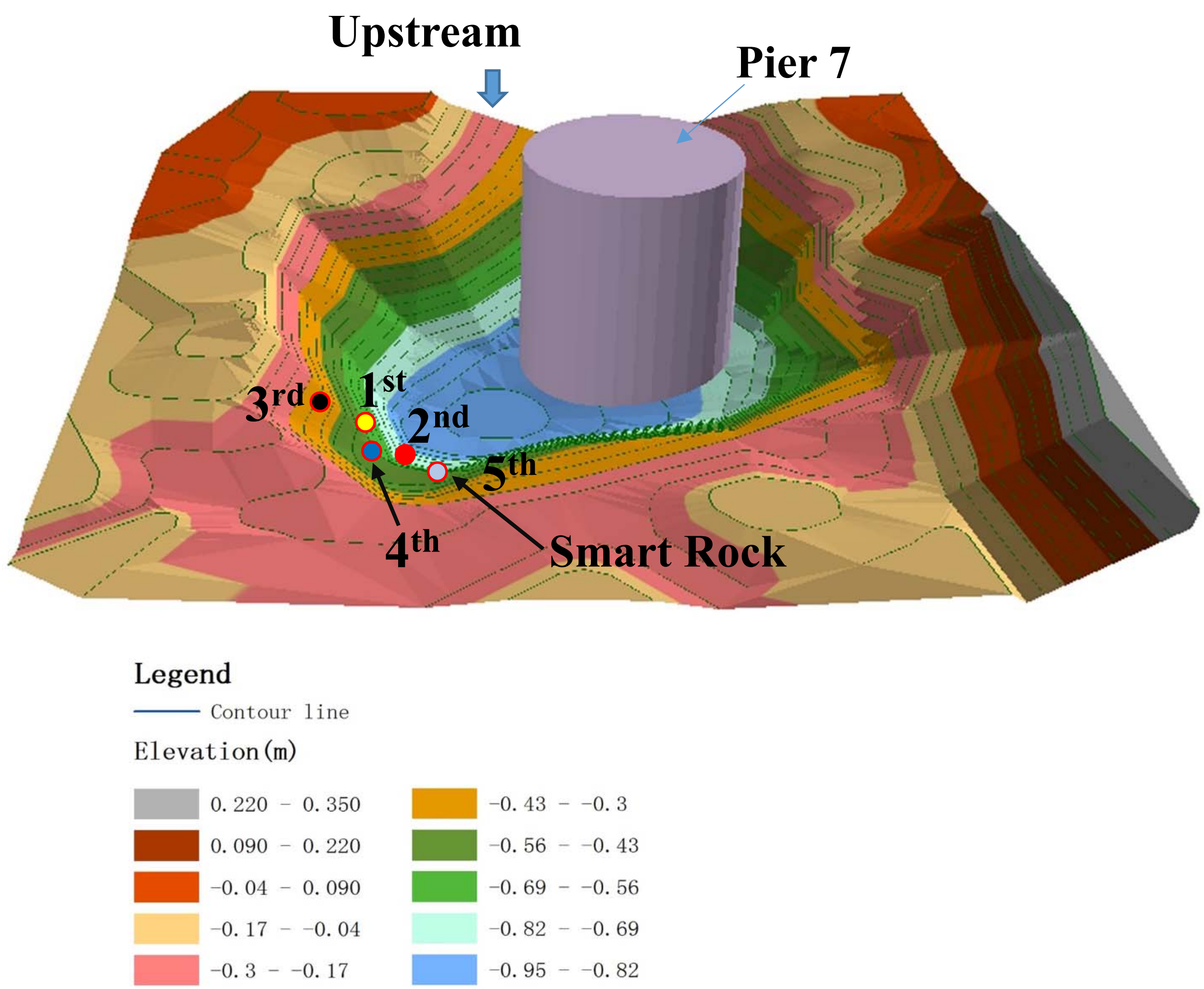
Field Studies

- **Rock Localization Accuracy**
  - **"Crane" vs. UAV Based Tests**

Monitoring Method	Date	Predicted Coordinate			Measured Coordinate			Error (m)
		X_m	Y_m	Z_m	X_m	Y_m	Z_m	
CRANE	11/6/2015	0.06	23.49	-3.03	0.09	23.24	-3.04	0.26
CRANE	4/14/2016	0.55	24.38	-3.21	0.37	24.60	-3.38	0.33
CRANE	10/20/2016	0.00	22.73	-2.59	0.00	22.63	-2.87	0.30
UAV	1/24/2018	0.02	23.50	-2.89	0.25	23.77	-2.93	0.36
UAV	5/10/2018	0.49	25.00	-2.81	0.45	24.78	-3.01	0.30

Field Studies

- **Smart Rock Movement over Time**



Concluding Remarks

- The smart rock deployed at the Roubidoux Creek Bridge was located satisfactorily. Both the conventional ‘crane’-based and the proposed UAV-based test methods give a prediction error of less than 0.5 m.
- The UAV-based test method can rapidly collect a dense array of magnetic field intensity at a bridge site. The large data set can potentially improve the accuracy of smart rock localization and movement prediction.
- The magnetic field interference of two smart rocks appears negligible when placed at 3 m apart. Future study will be directed to refine the understanding on the potential interference of two or more smart rocks in magnetic field measurement and rock positioning algorithm.

Acknowledgement

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- Thanks are due to Missouri Department of Transportation for making the bridge available for field study.
- Thanks are also due to MinerFly team at Missouri S&T for building UAVs and integrating measurement devices with them on behalf of the INSPIRE UTC.