AUTOMATED MFL SYSTEM FOR CORROSION DETECTION

Quarterly Progress Report
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ACCELERATED BRIDGE CONSTRUCTION
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Chapter 1 Introduction

According to the Federal Highway Administration there are about 700,000 bridges in the United States [1]. Based on federal and state regulations, bridges are typically inspected biannually. Commonly used methods of inspection include a combination of visual, nondestructive and structural health monitoring methods. Irrespective of the choice of available methods, bridge inspection is deemed labor intensive and requires significant sources. Also, due to safety concerns and accessibility issues, inspection ofsome bridges may be difficult.

Most of the bridges on the U.S. highway inventory consist of prestressed concrete bridges. The use of prestressing technology in the U.S. dates to about the early 50's. Prestressing is applied to a structure either through pre-tensioning or post-tensioning. Although, current practices in prestressing technology have improved significantly over the past few decades but the problem of corrosion persists. The corrosion of steel strand used in main load carrying elements can lead to catastrophic failures.

Due to challenges associated with corrosion, bridge owners are facing challenges since the corrosion in prestressing strands is not visible through visual inspection. Within the next few decades, it is expected that the condition of embedded steel elements within concrete bridges can pose serious safety problems. Discussion with state bridge engineers indicate that there is a tremendous interest in developing a methodology that can inspect the condition of embedded steel elements within concrete bridges in ways that are quick, economical and user-friendly for field application.

1.1 Nondestructive Methods for Bridge Inspection

Most of the bridges constructed in the U.S., constructed in middle of 20th century, have reached the end of their design life. The deterioration of some of these bridges has caused serious safety concerns which are reflected by poor bridge ratings in the national bridge inventory. As mentioned earlier, among the deterioration mechanisms, corrosion is of foremost concern [2].

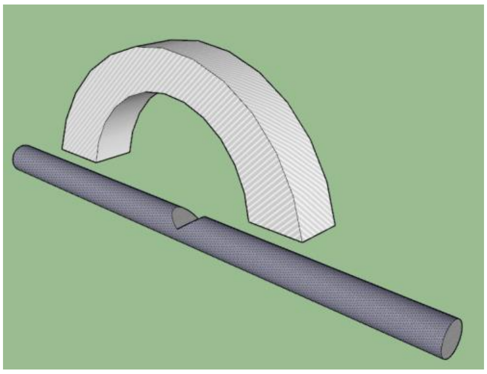
The inspection of prestressed concrete bridges poses major challenge since the steel strands are either embedded in concrete or externally located in ducts which are difficult

to access. The lack of proper and safe access to tendons adds difficulty to any inspection method. Additionally, these bridges generally have long spans, and the level of effort needed to inspect the entire bridge could be substantial. Visual inspections are supplemented with invasive methods, such as borescope, which have been used to assess the condition of strands in the PT ducts. However, these invasive methods are time consuming and costly and may compromise the durability of the tendons. Further, local corrosion damage to embedded steel elements does not generally result in visually noticeable changes to the external appearance of the bridge until it is too late. Therefore, an evaluation of these in-service bridges is important for safety and integrity of the bridge. Over the last 20 years, Principal Investigator (PI) has been working on the development of magnetic flux leakage (MFL) method for inspection of steel strands embedded in concrete bridges, such as segmental concrete or post-tensioned bridges. The principle of the method is briefly discussed in the next section and field challenges are ascertained
to develop a framework for improved inspection using automated approaches.

1.2 Magnetic Flux Leakage Method

MFL method has been used as nondestructive evaluation technique for a range of applications including bridges, pipelines, rail tracks, etc. The principal components of the MFL are comprised of a magnetic source (permanent or electromagnet) and flux sensors. The MFL method is a magneto-static measurement technique and is based on the application of an external magnetic field in vicinity of a ferromagnetic (steel) material to create magnetic flux lines to pass through the steel. The application of MFL to concrete structures is possible since concrete medium does not affect the measurements unless ferromagnetic impurities are present in the concrete [3].

MFL method works by magnetizing a strand under an exciting magnetic field and the magnetic flux predominantly remains within the strand. In the presence of a geometric discontinuity such as a part of a corroded strand with loss of cross-section, the magnetic flux is deviated (leakage) and can be detected by magnetic sensors such as hall effect (HE) sensors (*Figure 1.1).* The HE sensors are made with semi-conductor crystals which when excited by a passage of current perpendicular to the face of the crystal, responds by developing an output voltage proportional to the magnetic field strength. Analysis of the leakage flux output signals can be used to detect the location and the size of the defect. The extent of metal loss can be identified by the corresponding intensity of the defect leakage flux signals [4].



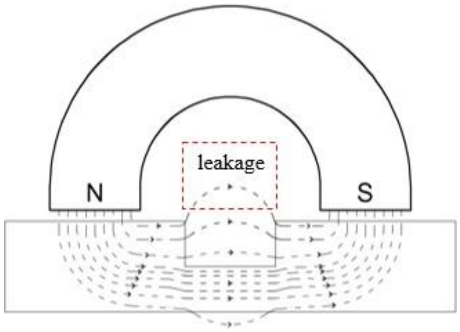


Figure 1.1: Photographs of test setup.

The method first was developed in late 1970s and has been subject to ongoing evaluation as sophistication of electronic instrumentation and data analysis techniques have improved. The two main components of the MFL system are the sensing and magnetizing units. The measurement of the signal is performed using an active or remnant method. A few field applications of MFL method is shown in *Figure 1.2* which employs different magnetizing and signal measurement systems.

Figure 1.2: MFL application using manual equipment (Photo courtesy Prof. Bernd Hillemeier).

1.3 Prior Example Results

This section provides a brief summary of one of the test that demonstrates the manual application MFL method. *Figure 1.3* shows the segments of a segmental concrete bridge that were saw cut and brought to Florida International University (FIU) for the development of MFL method. These box girder sections contain an empty duct which is used as a test bed for the MFL method.

Figure 1.3: Segments of segmental concrete bridge at FIU.

The un-grouted empty ducts provide an opportunity to simulate different test conditions. A group of strands, with known damages, were placed inside this duct and testing was carried out to assess the capabilities of the method. *Figure 1.4* shows the MFL system which includes a permanent magnet, magnetic sensors, linear encoder, data acquisition system, and power supply.

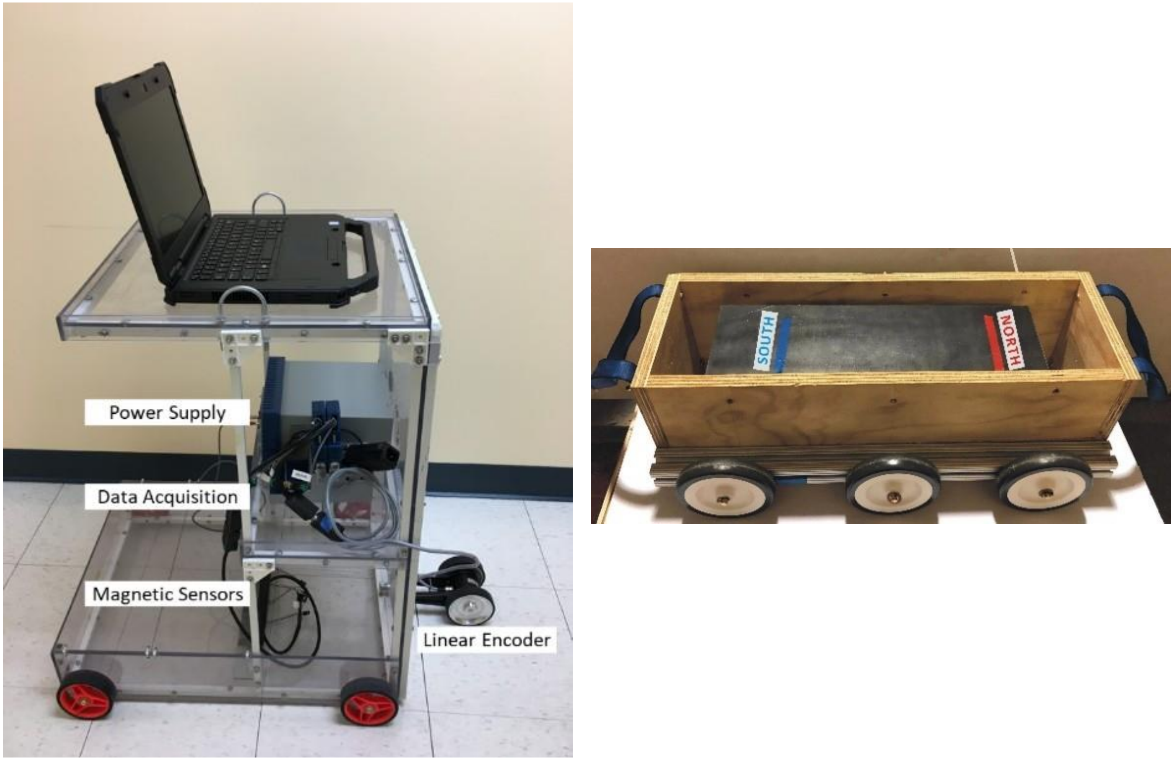


Figure 1.4: MFL equipment.

Figure 1.5 shows the location of the main strands, the location of secondary strands and the location of rebars with the location of the defect. The strands were initially magnetized from the bottom side with a depth of 7 inches and then the strands were again magnetized by keeping the depth of the magnet 3 inches from the bottom surface of the segment.

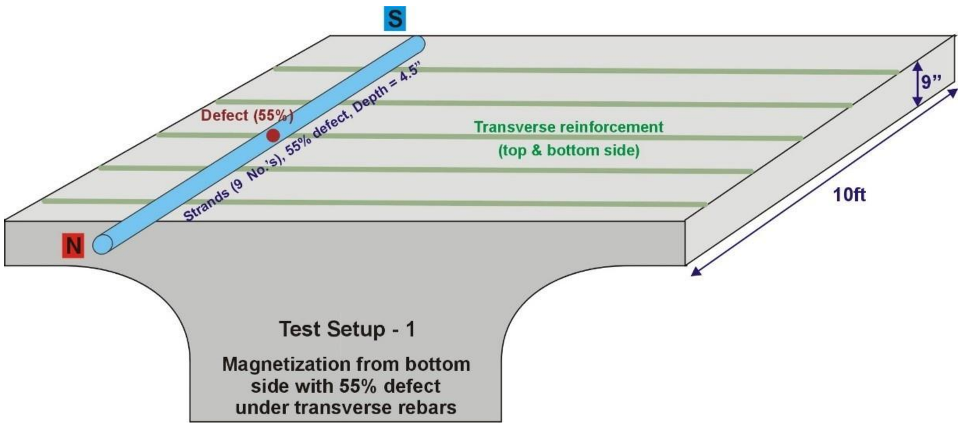


Figure 1.5: Location of defects in post-tensioning strands withtransverse reinforcement.

The first test was performed by keeping the location of the defect in such a way that the transverse reinforcement is passing just above and below the defect. The tendon contained a group of nine strands and the defect was introduced in five strands which makes the defect percentage to 55%. The MFL signal is shown in *Figure1.6.* The signal clearly shows the location of the defect and the transverse rebars present above and below the defect are not affecting the signal. A series of testing on the bridge segment has shown that the methodology is effective when defect percentage is more than 20% of steel cross-sectional area.

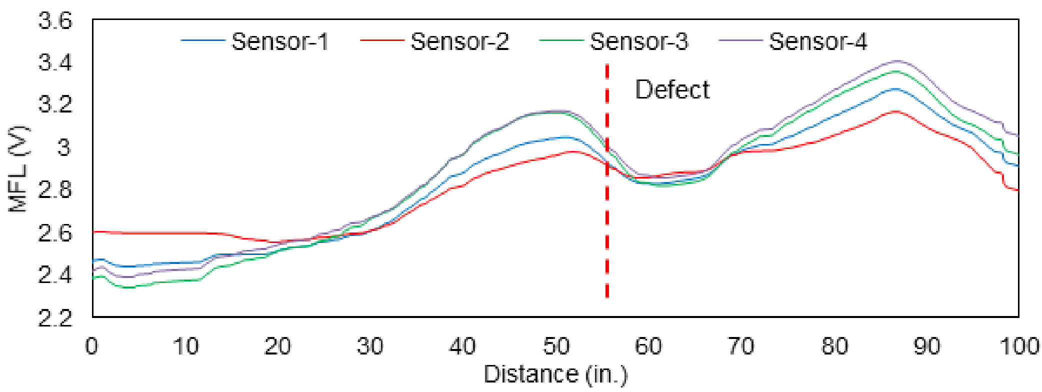


Figure 1.6: Location of defects in post-tensioning strands with transverse reinforcement.

1.4 Problem Statement

The MFL method is not new and has been used by research and industry professionals for past few decades. For accessible bridge components, the manual operation can be accomplished without the need of any specialized equipment or support mechanisms. However, for majority of the bridges, the components with prestressing systems are difficult to access. Besides these challenges, the safety protocols may require partial or complete closure of traffic during testing.

The PI of the project has recently developed a testing methodology which can reduce the interference of signals from mild reinforcement. Although the method has shown promising results, but the field implementation is still challenging. The method essentially consists of magnetizing the tendon and then taking MFL signal measurement concurrently or independently with the magnetizing unit. For majority of applications, magnetizing of the tendons can be carried out from accessible area of the bridge. The main challenge is to perform signal measurement which can be cumbersome and difficult. *Figure 1.7* shows few photographs of the field challenges during signal measurement [5]. In addition, the tendons in prestressed structures are typically placed in a straight, harped or a parabolic profile. This arrangement of tendons increases the level of difficulty in implementing the MFL method. The complex profiles of these tendons limit the use of clamped, climbing assemblies and rotary systems. There is a need to develop an automated approach for signal measurement using a combination of robotics, unmanned automated aerial drones and advanced image and data processing techniques.

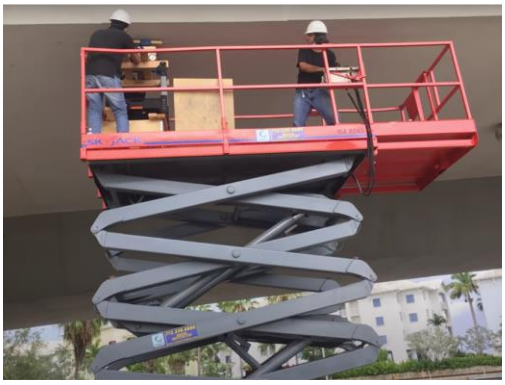



Figure 1.7: Challenges for field implementation [5].

Automation in MFL system has been introduced for applications such as gas pipes, cable-stay applications, external posttensioned tendons etc. One common example of the use of robotic MFL for external PT system is the clamped module which moves along the external PT tendons or cable stayed bridges. The clamped modules are remotely operated and can move along the cables. Another common robotic system is used for gas pipe. Although few applications of automation in MFL systems can be found for external components but there has been limited research on MFL for internal tendons.

1.5 Research Approach and Objectives

In view of practical challenges for bridge inspection, the use of an unmanned aerial vehicle has evolved in recent years. This method offers use of either being autonomously or remotely piloted aerial vehicles. Extensive research data and commercial equipment is available on use of unmanned drones for bridge inspection. These existing unmanned vehicles use an array of sensing systems to detect damages including 3D surface reconstruction, augmented reality, infrared thermography, and other high-definition imaging [6,7].

The main objective of this project is to automate the MFL technology that is developed to inspect the health of steel elements within concrete bridges. This project aims at developing an unmanned aerial vehicle for bridge inspection using the MFL method. The proposed project will result in an improved method for inspection of prestressed bridges and provide bridge owners with state-of-the-art technology which can be extended to other bridge types.

1.6 Description of Research Project Tasks

The following is a description of tasks to be carried out under this project:

***Task 1 - Development of an automated approach for MFL*:**

The use of various small robots in conjunction with wireless data acquisition with robots controlled from a distance is the solution for automating the procedure. Under this task, the elements of the current MFL system will be modified to make use of wireless sensors in conjunction with the use of small robots.

***Task 2 - Laboratory validation of the new automated system for MFL*:**

In this task, laboratory validation of the efficacy of the automated system utilizing small robots and wireless data acquisition system. The laboratory test will be conducted on the bridge segments at FIU as shown in *Figure 1.3*.

Progress: Several laboratory tests were performed using the wireless automated system to check the efficiency of the robot and its behavior to move on horizontal and vertical surfaces. The results of the system were satisfactory but need further testing on the bridge segment.

***Task 3 - Field validation of the new automated system for MFL*:**

In this task, field validation of the efficacy of the automated system utilizing small robots and wireless data acquisition system. The PI will work closely with FDOT to identify a bridge candidate for the deployment of the new system for field validation.

Task 4 - Final Report:

A final report will summarize the findings of this proposed research.

Chapter 2 Development of an Automated Approach for MFL

During the conceptualization stage, different designs of an automated MFL system were considered. The basis of these designs was to provide some level of autonomous control to the system and to reduce the human interference during operation. Also, based on field experiences with the MFL testing, modifications were made to build an automated vehicle or aerial drone which can overcome practical constraints. The following sections provide a brief summary of efforts to date regarding automation of the MFLsystem.

2.1 Wall Climbing Robot

One of the first prototype developed at FIU consisted of a wall climbing robot. A small robot, as shown in *Figure 2.1,* has been utilized as first prototype and the MFL system with wireless data acquisition was mounted on it. The robot used a negative pressure- thrust suction method to climb vertically on walls.

Figure 2.1: Suction based wall climber.

2.2 Drone for MFL inspection

In the next phase, an aerial vehicle was designed. The selection parameters for the design of the drone was based on a number of factors. Following considerations were studied to design the drone:

- Flight Time: Longer flight time allows for a more efficient and comprehensive bridge inspection as it minimizes interruptions to change the drone batteries.

- Payload capacity: Payload is important as it allows the drone to carry additional attachment such as sensor systems.

- Altitude and Range: The preliminary aerial vehicle is intended for bottom soffit of bridges located at a lower altitude. This will minimize wind disruptions and stabilize the system. For bridge inspection, the range of some structures are located over water; therefore, a long-range remote control is required to inspect such structures.

Based on these parameters, a design of an aerial vehicle was carried out. Based on these considerations, a drone was designed with four propellers. The conceptual diagram of the drone is shown in *Figure 2.2.*

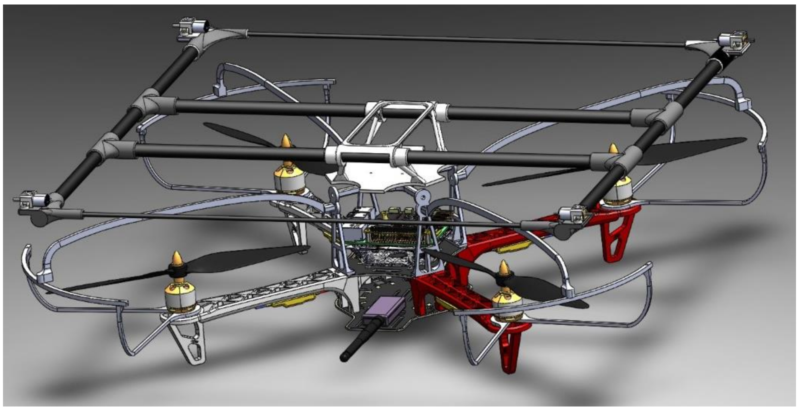


Figure 2.2: Conceptual diagram of drone.

The four corner wheels are mounted to provide greater stability, speed, payload capacity and to drive the drone on walls and roof. The fabricated drone is shown in *Figure 2.3.*

Figure 2.3: Fabricated drone for MFL testing.

The drone was simulated using 3D simulator Gazebo which has the ability to simulate drone accurately and efficiently. The simulation of the drone is shown in *Figure 2.4* while the flying drone is shown in *Figure 2.5.* The measurement system will then be installed on top of the drone for signal measurement.

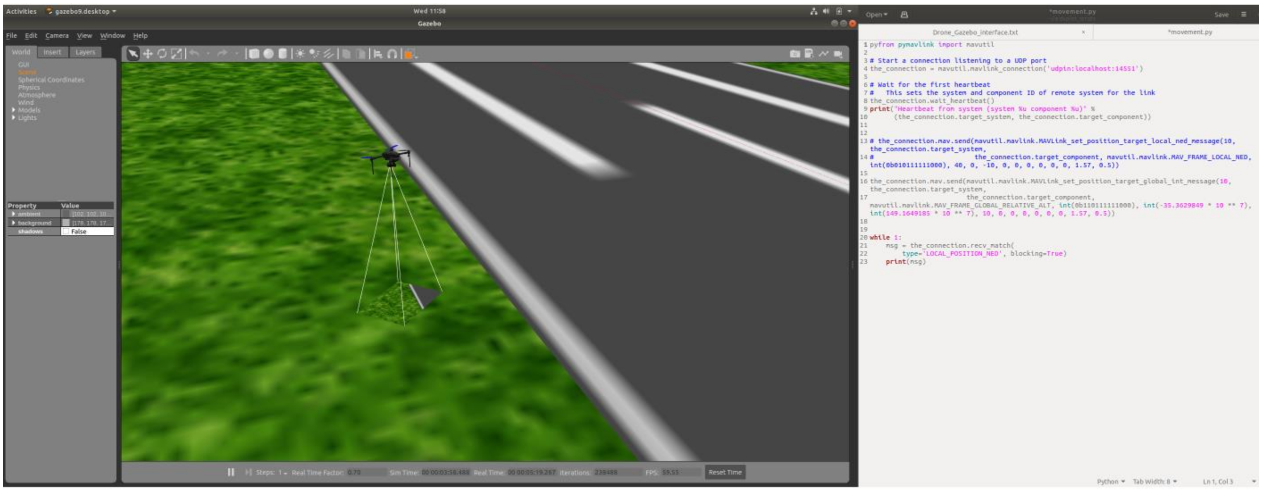


Figure 2.4: Simulation of drone in Gazebo simulator.

Figure 2.5: Flying drone in FIU.

2.3 Progress and Schedule

The schedule of the project is shown *Figure 2.6.*

Item	% Completed
Percentage of Completion of this project to Date	75%

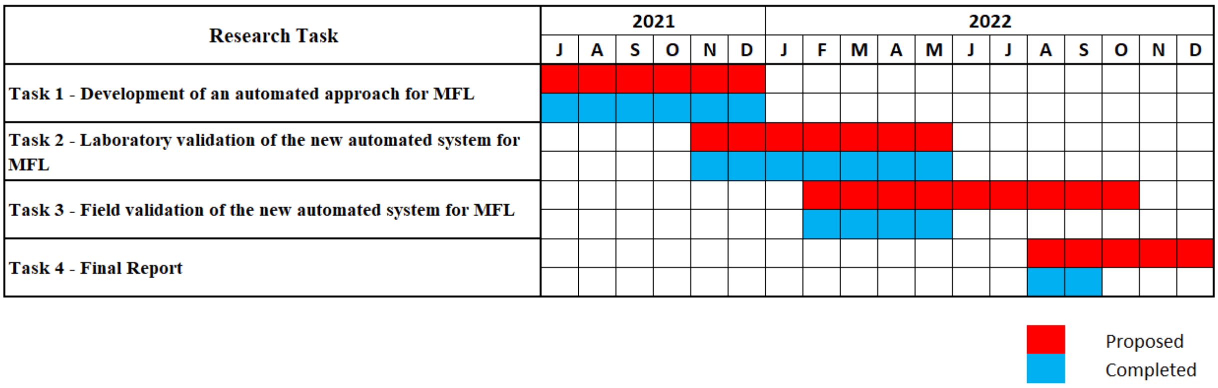


Figure 2.6: Schedule of the project.

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