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THE DEPARTMENT OF
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ENGINEERING

DEPARTMENT OF
ELECTRICAL &
COMPUTER ENGINEERING

NSF

CPS: Synergy: Collaborative Research: Designing semi-autonomous networks of miniature robots for inspection of bridges and other large infrastructures

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Objectives

Visual identification of structural flaws is quite valuable not only to predict an imminent collapse of a bridge, but also to determine effective precautionary measures and repairs.

In this project, we will pursue a three-year basic research program to establish new design and performance analysis principles, and technologies for the creation of a semi-autonomous network of small mobile robots to aid visual inspection of civil infrastructure. This network will aid a human surveyor to remotely and routinely inspect structure areas such as a typical girder assemblage that supports the decks of a suspension bridge. Methods to be used: The goals mentioned above will be addressed via a multidisciplinary basic research effort in hardware, algorithm design and performance analysis. In order to achieve this goal, our team includes one researcher (CTO of Resensys LLC) in the area of bridge monitoring, and 3 faculty from 2 departments. Our team's expertise covers all the key basic research areas of the project.

Importance of Bridge Monitoring

Visual identification of structural flaws is quite valuable not only to predict an imminent bridge collapse, but also to determine effective precautionary measures and repairs.


(a) Bending of a metal plate that was detected prior to the collapse.

(b) Fracture that was later found to be a major cause of the collapse.

Structural flaws of I-35W bridge

Problem Formulation

We will pursue a three-year basic research program to establish new design and performance analysis principles, and technologies for the creation of a semi-autonomous network of small robots to aid visual inspection of civil infrastructure. The main idea is to use such a network to aid a human surveyor in remotely and routinely inspecting structure areas such as a typical girder assemblage that supports the decks of a suspension bridge.
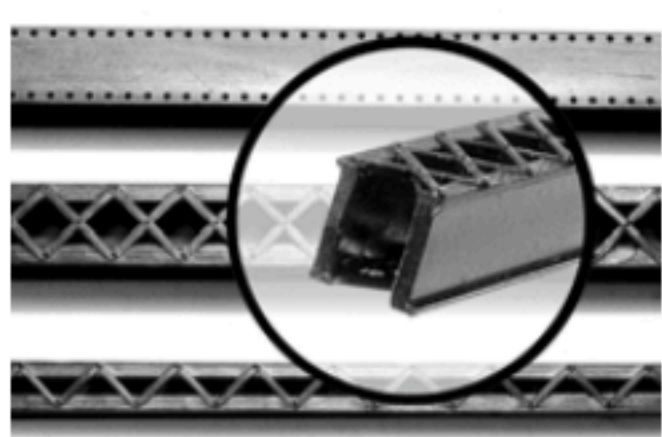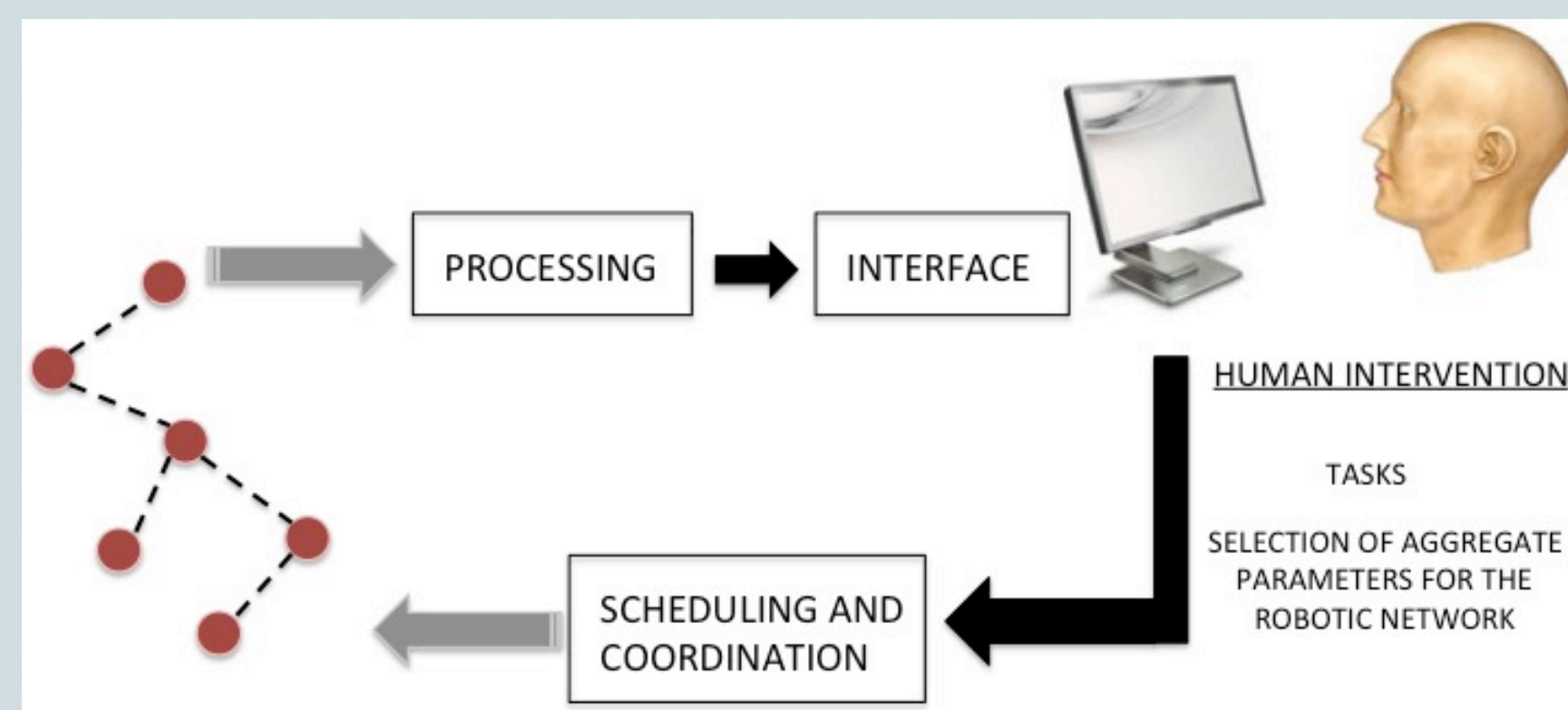

(a) Example of an old open girder.
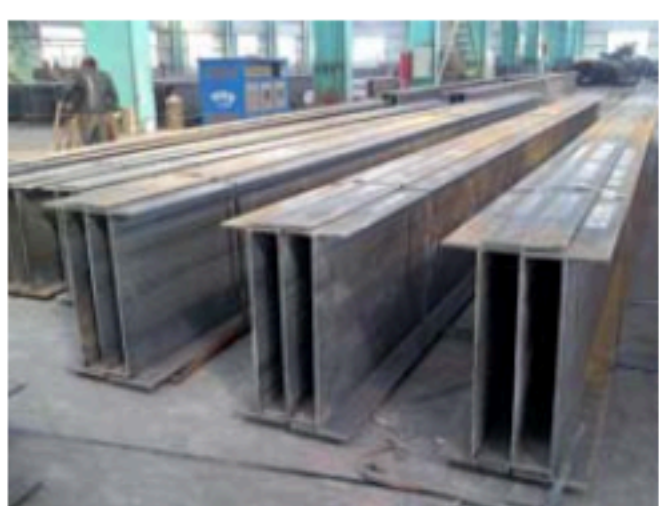
(b) Modern closed girder.

(c) Girder assemblage.

System Description:

The role of the proposed network of small robots is to acquire sensory information, such as images, and send it to the base stations for processing and feature extraction. The network is mobile and semi-autonomous, and it will have self-organizing capabilities to carry out the inspection tasks.
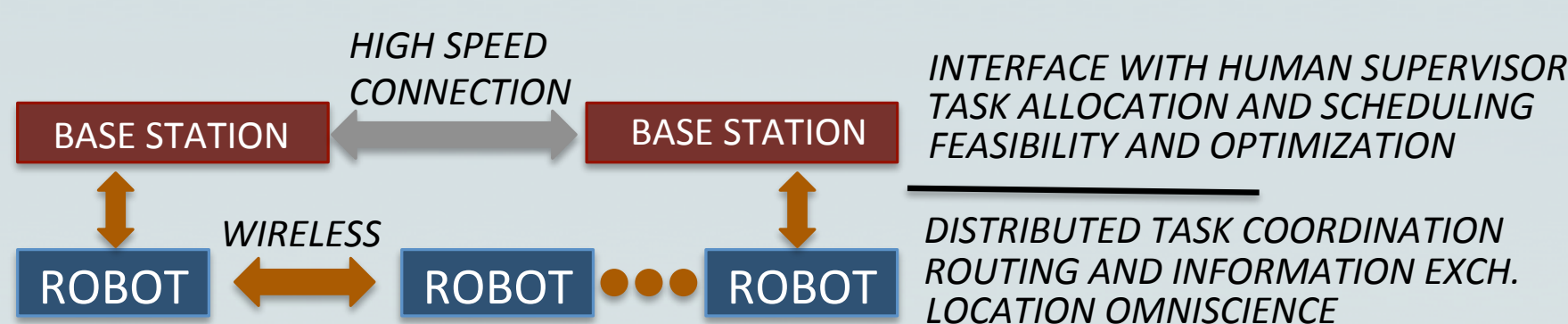
## Networked coordination, team decision and information collection:
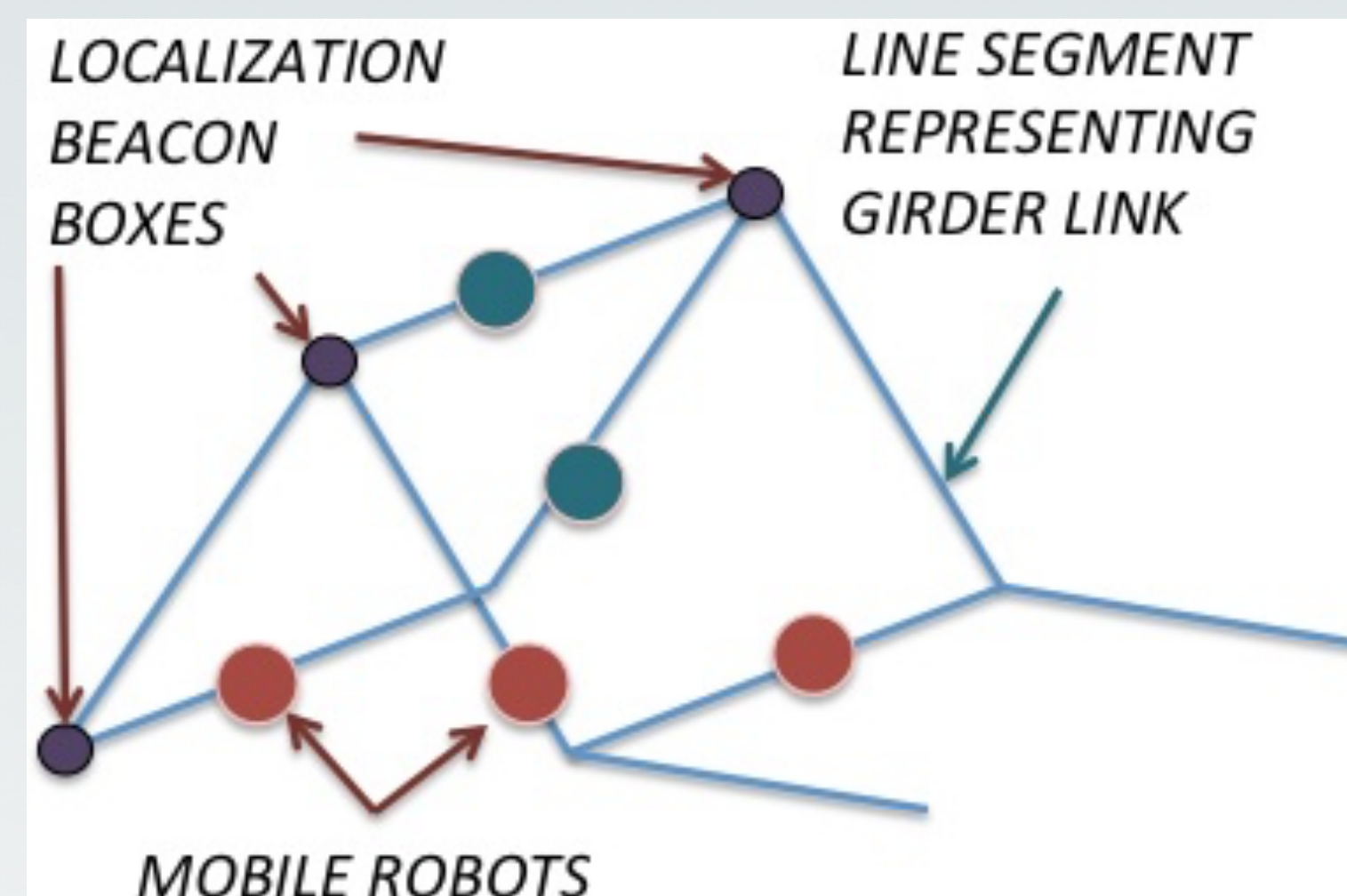
The system will be designed to execute a group survey mission, for which the user specifies an area to be surveyed, number of robots assigned, duration and which measurements should be collected (vibration, tilt, temperature) in addition to still images. The following are the mission steps that must be executed to accomplish the mission:

1. The robots will first follow the precompute schedule to inspect the bridge.
2. If something unexpected occur, for instance, robot failure or cost greatly exceed the precompute estimation, the robots will communicate with base station and other robots to modify the schedule.
3. The robots will report back to BSs when done.

## Task Scheduling for Human-Assisted Inspection Systems

We formulated a new class of problems in which a human operator assists a semi-autonomous inspection system. New tasks arrive to a queue in accordance with a stochastic process which are assigned to a human operator by a scheduler. The efficiency of the human operator depends on an action-dependent state of the operator, such as recent workload or fatigue level. And it evolves on the basis of the history of task assignments to the human operator by the scheduler. We investigate the problem of designing a good scheduling policy with simple structure for two different objectives —maximizing long-term service rate and minimizing long-term workload for human operator (for fixed task arrival rate). We designed an optimal scheduling policy with a threshold on action-dependent state for a single-queue system handling homogeneous tasks and a double-queue system servicing two types of heterogeneous tasks (images vs. videos). We also developed a near-optimal scheduling policy that minimizes the (long-term) fraction of time the human operator must work on tasks, while maintaining system stability.

Path Planning for Inspection
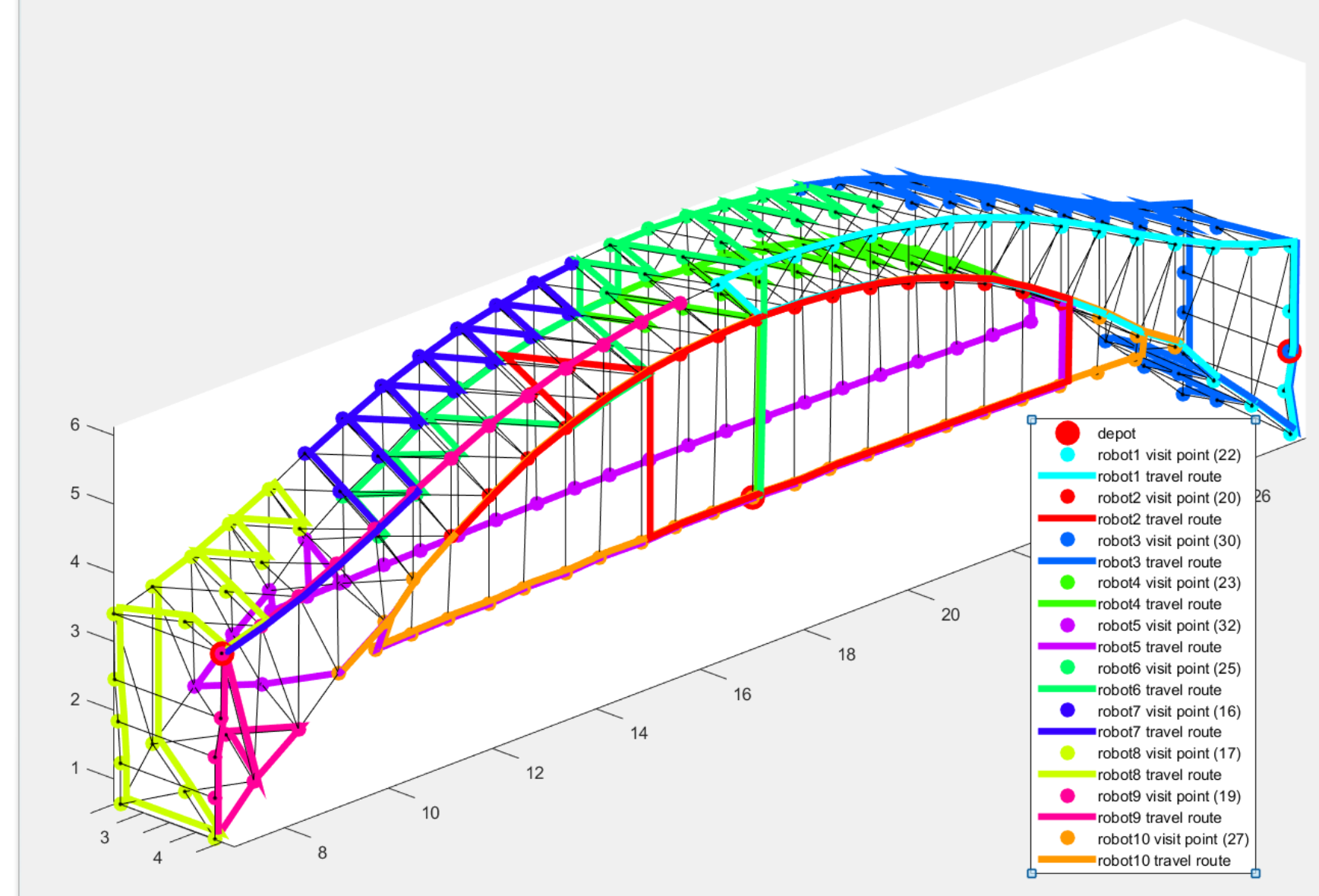
We studied the problem of planning the deployments of (mobile) robots for bridge inspection. The robots are assumed to be initially stationed at multiple depots placed throughout the bridge. The problem is formulated as a min-max cycle cover problem in which the vertex set consists of the sites to be inspected and robot depots, and the weight of an edge captures either (i) the amount of time needed to travel from one end vertex to the other vertex or (ii) the necessary energy consumption for the travel. In the first case, the objective function is the total inspection time, whereas in the latter case, it is the maximum energy consumption among the deployed robots. We proposed a novel approximation algorithm with approximation ratio of $5+\varepsilon$, where $0<\varepsilon<1$. In addition, the computational complexity of the proposed algorithm is shown to be $O(n^2+2^{d-1}(\log(n)+\log(1/\varepsilon)))$, where n is the number of vertices and d is the number of depots.

The numerical results (to the right) demonstrate that the maximum cost of the proposed algorithm is at most 2.5 times the lower bound for the optimal value.
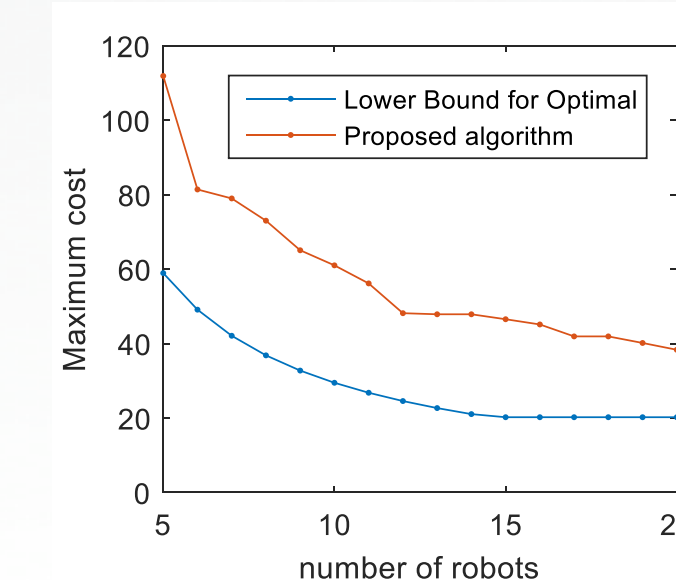

Locomotion:

BRIDGE Bot is a 158 g, 10.7 x 8.9 x 6.5 cm, magnetic-wheeled robot able to securely adhere to magnetic bridges in any orientation. Its flexible, multi-material legs allow it to complete a wide range of plane transitions. In the graphic (bottom right), green regions indicate transitions the robot can currently complete. A thrust-driven wall inspecting robot was also developed in order to operate on non-magnetic walls/bridges for the purpose of imaging structural malfunctions. The robot is controlled using Raspberry Pi and has 4 independently controlled wheels.

Air flow
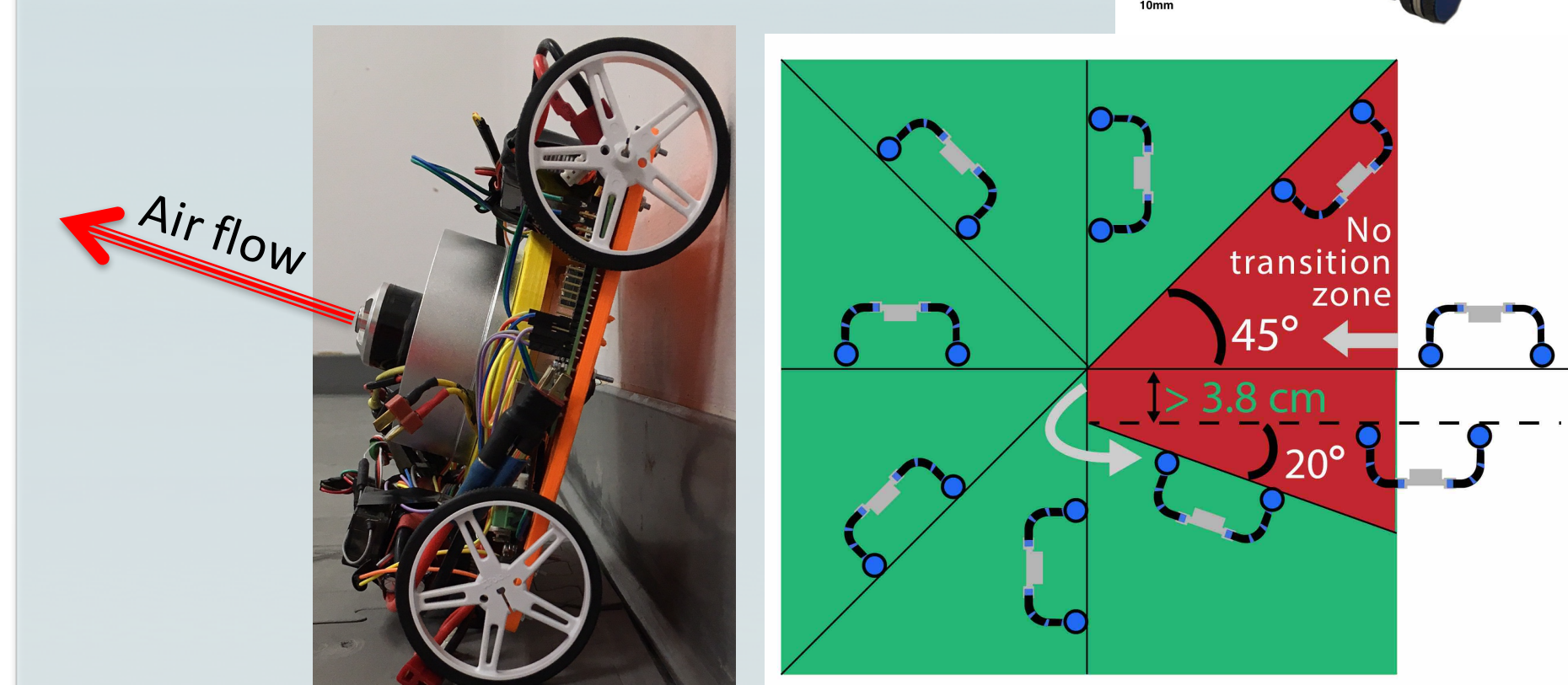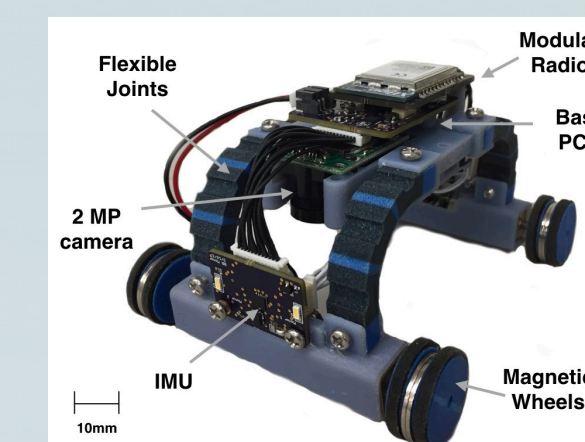
Work on electroadhesives has focused on using an energy balance approach (JKR model) to understand adhesion and failure in fabricated polymer-based electroadhesives. The plots shown are for axisymmetric tact tests using a spherical and cylindrical probe.
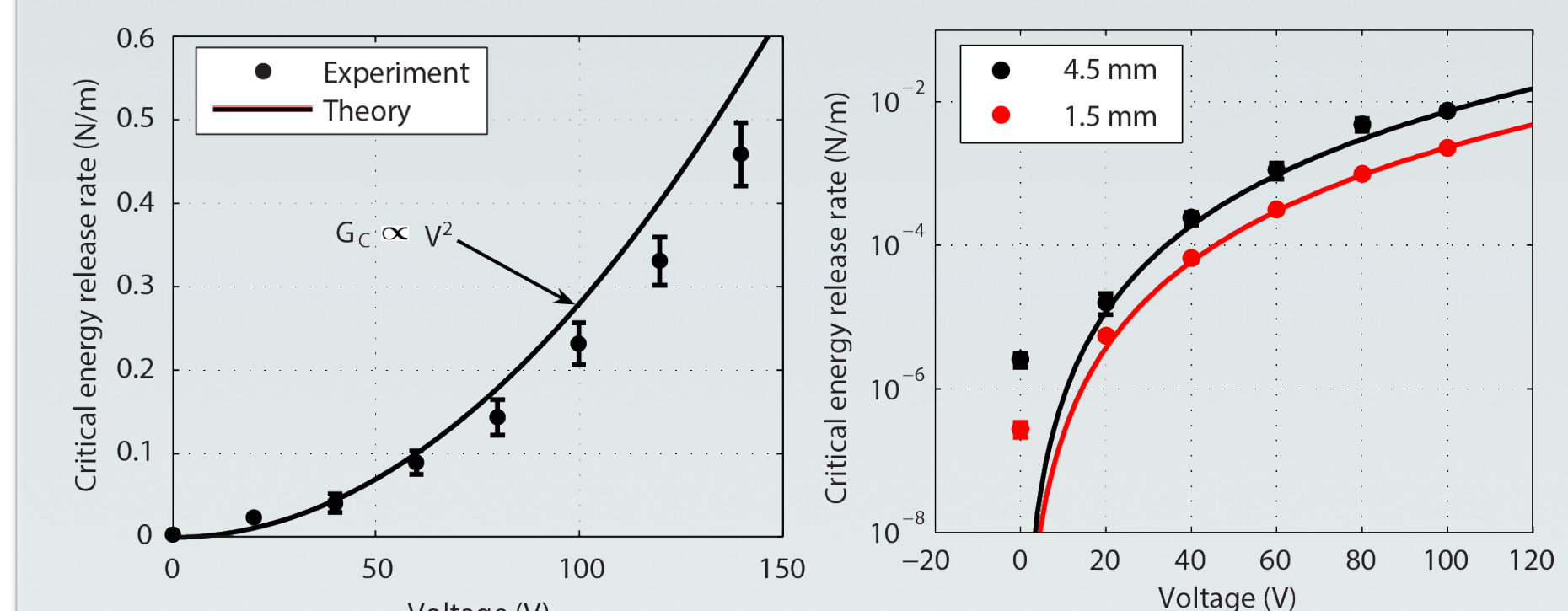
Application Scenario:

May 1st, 2017, 18:00 UTC
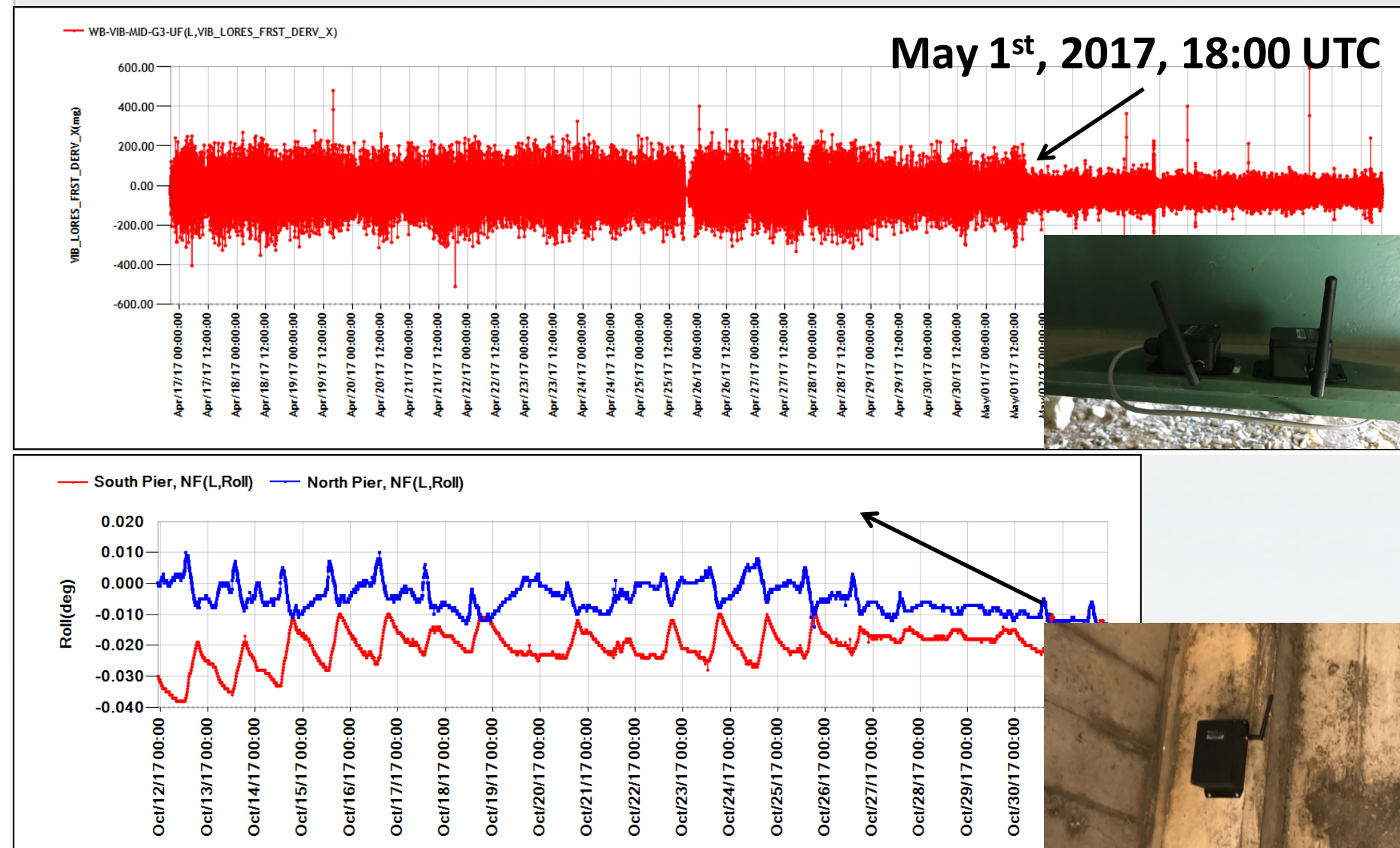
The plots above demonstrate fixed node sensing systems for detecting structural malfunction. The first plot shows acceleration data from girders under a bridge deck from April 16, 2017 to May 7th, 2017. Vibration pattern in the structure is due to traffic and heavy trucks. A noticeable change in pattern, which corresponded to a structural malfunction, was observed on May 1st. The second plot gives tilt readings from two devices deployed to monitor the structural integrity of a scour critical bridge. The monitoring is ongoing.