MARYLAND ROBOTICS CENTER
THE INSTITUTE FOR SYSTEMS RESEARCH
THE DEPARTMENT OF MECHANICAL ENGINEERING
DEPARTMENT OF ELECTRICAL & COMPUTER ENGINEERING

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 pursued a three-year (plus two no-cost) 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 may 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 were 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.

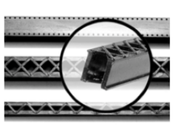
(a) Bending of a metal plate that was detected prior to the collapse.

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

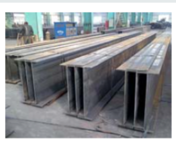
Structural flaws of I-35W bridge

Problem Formulation

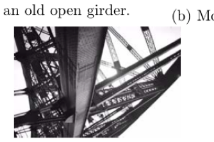
We pursued a three-year basic research program to establish new design and performance analysis principles, and technologies for the creation of a semi-autonomous network of small robots to aid visual inspection of civil infrastructure. The main idea is to use such a network to aid a human surveyor in 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.

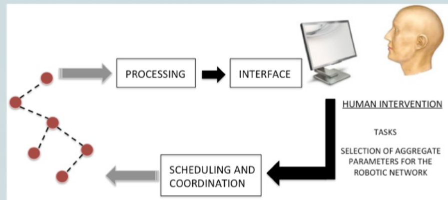


(b) Modern closed girder.

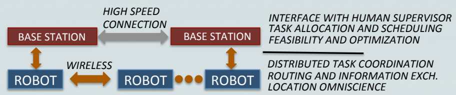


(c) Girder assemblage.

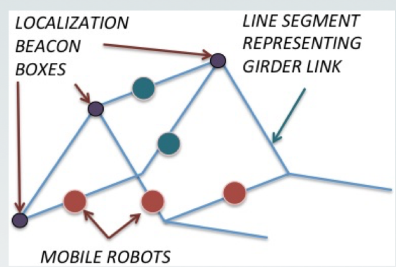
System Description:



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.



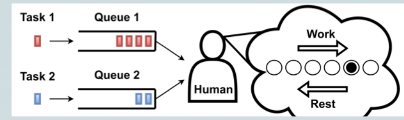
Networked coordination, team decision and information collection:



We designed systems and algorithms to implement group survey missions, 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 precomputed schedule to inspect the bridge. Localization should not rely on GPS or vision-based tracking. We developed and lab tested a new framework and algorithms for UWB localization in narrow spaces. Existing methods would, in general, perform very poorly due to near-singularities.
2. If something unexpected occurs, for instance, robot failure or cost greatly exceed the precomputed 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

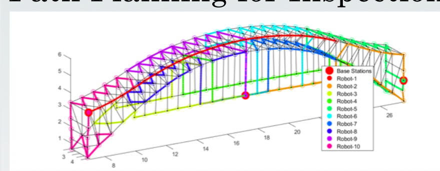


We formulated and provide solutions to a new class of problems in which a human operator assists a semi-autonomous inspection system. New tasks arrive to a queue which are assigned to a human operator by a scheduler. The efficiency of the human operator depends on an action-dependent state of the operator, such as the recent workload or fatigue level. We designed an optimal scheduling policy for a multi-queue system handling heterogeneous tasks (images vs. videos) to maximize throughput for any arrival rate. 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.

Transmission Policies for Energy Harvesting Sensors

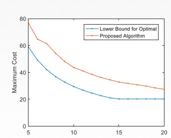
Consider a remote sensor with energy harvesting ability (such as a solar panel) and is monitoring an LTI system. The sensor is equipped with a battery and communicates with the base station by sending wireless packets. The packet-drop probability is affected by the battery level. We show that it suffices to search for deterministic transmission policies which only use the info of battery level to determine whether the second moment of the estimation error can be bounded or not. Also, we identify an important case in which the search can be further narrowed to threshold policies.

Path Planning for Inspection

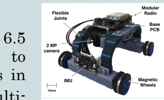


We studied the problem of planning the deployments of (mobile) robots for bridge inspection. The robots are assumed to be initially stationed at multiple depots placed throughout the bridge. The problem is formulated as a min-max cycle cover problem in which the cost can represent total inspection time or maximum energy consumption for robots. We proposed a novel approximation algorithm with an approximation ratio of 4+(d-1)/k where d is the number of base stations, and k is the number of robots. In addition, the computational complexity of the proposed algorithm is shown to be $O(n3)$, where n is the number of vertices.

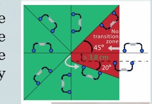
The numerical results (to the right) demonstrate that the maximum cost of the proposed algorithm is at most 1.7 times the lower bound for the optimal value.



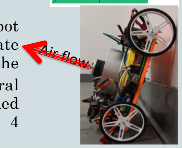
Locomotion:



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, green regions indicate transitions the robot can currently complete.

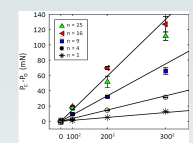


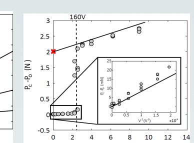
A thrust-driven wall inspecting robot was also developed in order to operate on non-magnetic walls/bridges for the purpose of imaging structural malfunctions. The robot is controlled using Raspbery Pi and has 4 independently controlled wheels.

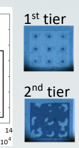


Work has been done to use JKR theory to develop a design framework where electroadhesion can take advantage of contact splitting. Textured electroadhesives with arrays of spherical bumps to contact surfaces were developed to improve electrostatic force. The figure below (left) shows the electrostatic force for textured devices with varying number of spherical bumps.

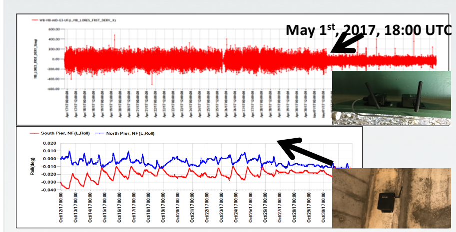
These textured devices can also be modified to obtain even larger adhesion ranges by having multi-tiered contact areas. Different tiers of contact can be engaged once the mechanical and electrical preloads reach a threshold. The figure below (right) shows the tack tests for a textured device with 9 spherical bumps for the 1st tier for contact. The 2nd tier is the area around the bumps, which engages at voltages larger than 160V.







Application Scenario:



The plots above demonstrates 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.