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

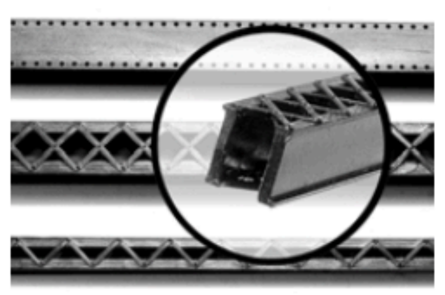
Visual identification of structural flaws is quite valuable not only to predict an imminent bridge collapse, but also to determine effective precautionary measures and repairs.

(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.

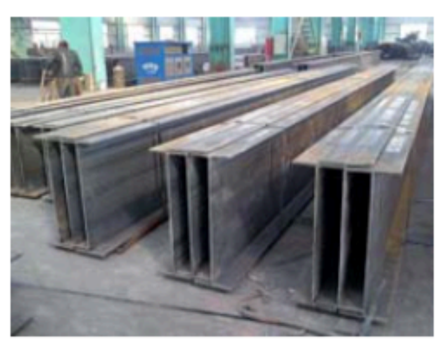
Structural flaws of I-35W bridge

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.



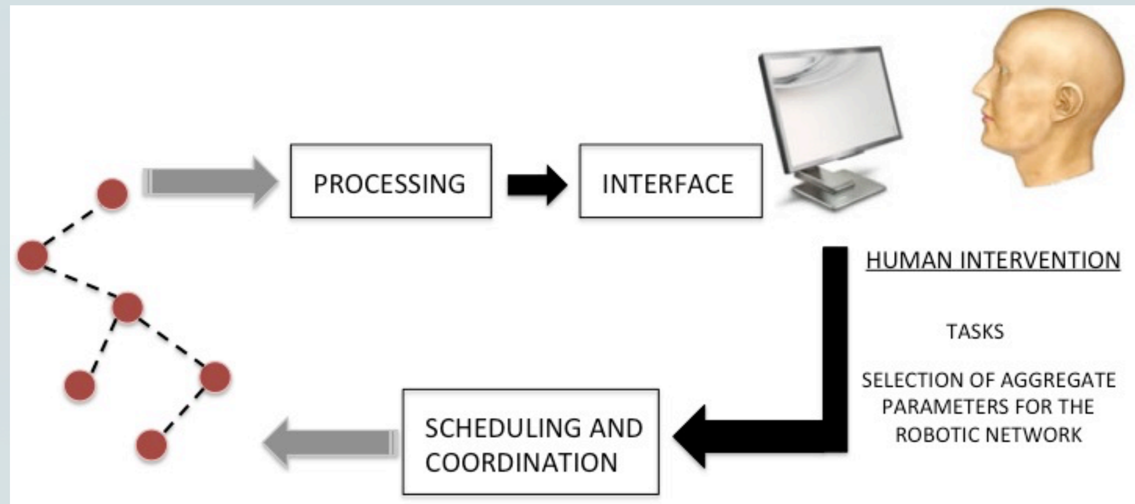
(a) Example of an old open girder.



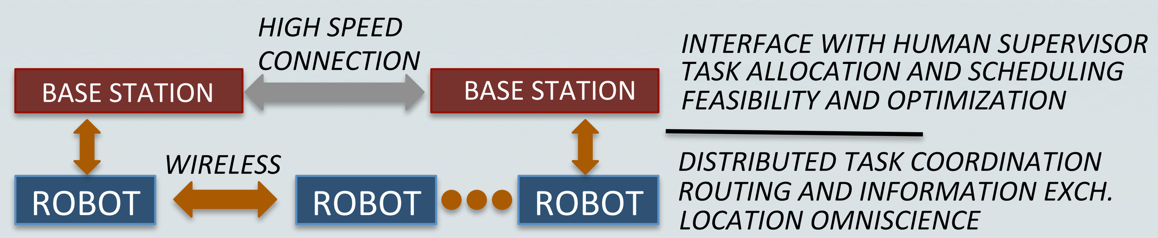
(b) Modern closed girder.

(c) Girder assemblage.

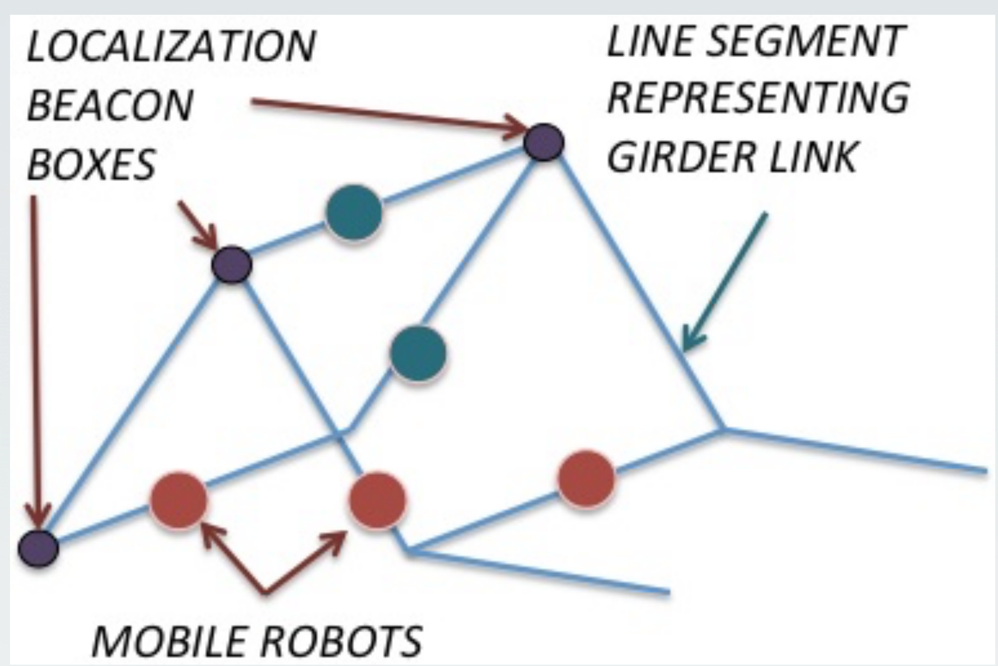
System Description:



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:



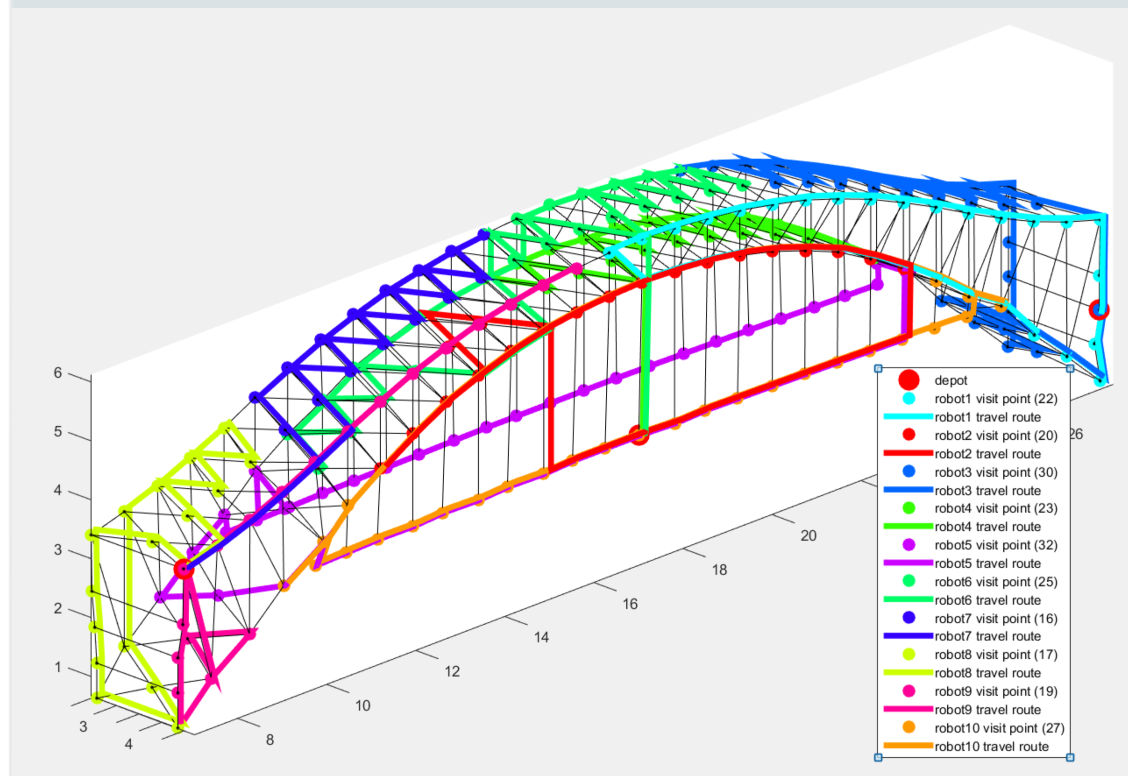
The system will be designed to execute a group survey mission, for which the user specifies an area to be surveyed, number of robots assigned, duration and which measurements should be collected (vibration, tilt, temperature) in addition to still images. The following are the mission steps that must 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.

Robot-Deployment Planning

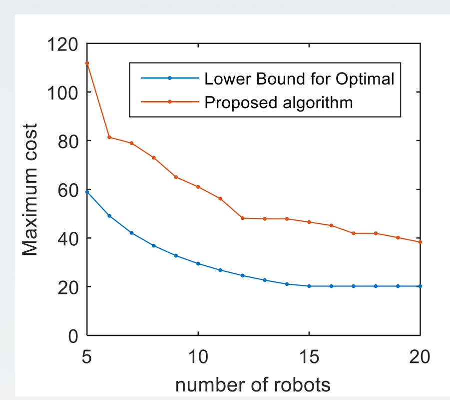
We studied the problem of planning the deployments of (mobile) robots for bridge inspection. The robots are assumed to be initially stationed at multiple depots placed throughout the bridge. The problem is formulated as a min-max cycle cover problem in which the vertex set consists of the sites to be 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.

Numerical Results



We use the Sydney Harbour Bridge for our numerical studies. Three depots are placed on the bridge – one at each end and the other in the middle of the bridge. Inspection points are assumed to be the joints in the bridge. The amount of time or the required energy consumption for traveling a beam is proportional to its length, and there is a fixed cost of inspecting a joint.

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.

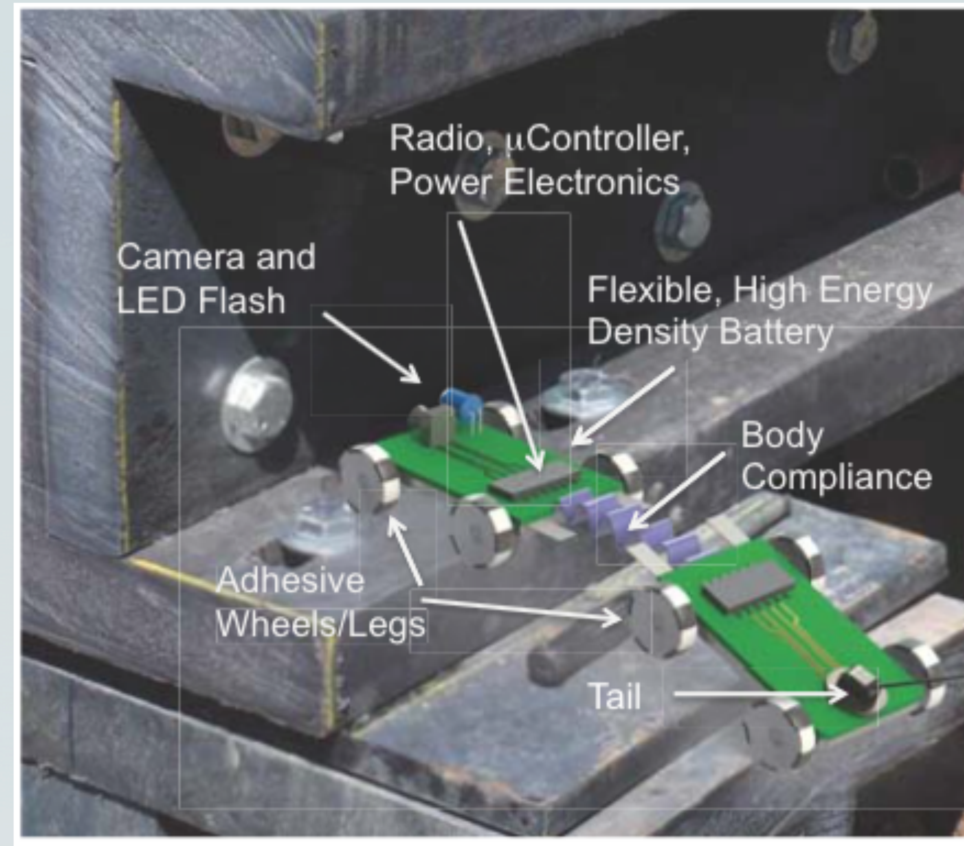


Contact-based localization

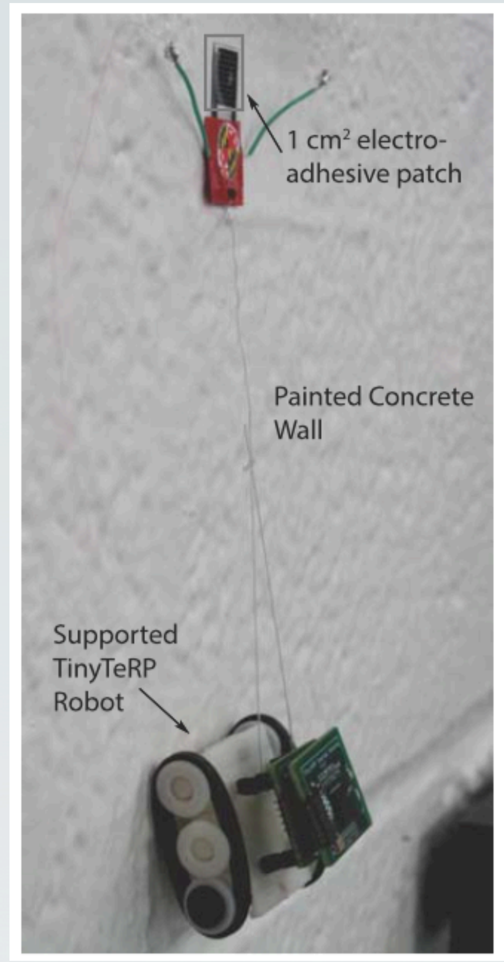
We are also developing algorithms that use contact events among the robots and collisions with walls and obstacles to improve localization within the structural portions of the bridge, where GPS and other methods are not viable.

Locomotion:

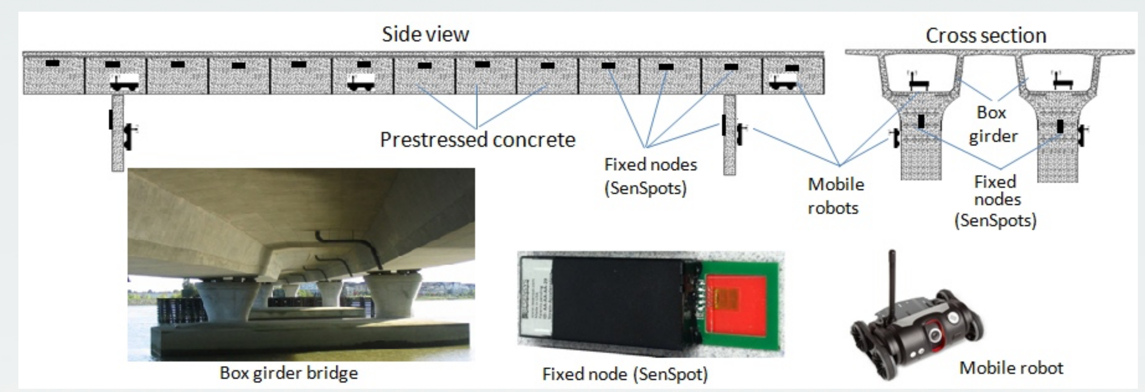
The proposed locomotion capabilities are illustrated in the figure below. These robots are small, dynamic, and utilize a compliant backbone with adhesive wheels/legs that allow them to climb both steel and concrete.



The first locomotion innovation is the use of electroadhesive pads to provide substantially greater compliance and adhesion for maneuvering on common bridge surfaces from painted steel to con-crete.



Application Scenario:



The figure shows our approach to monitoring concrete box girders on a bridge: First, a SenSpot sensor is attached to each prestressed concrete piece. When a crack develops at the connection points of prestressed concrete, it will lead to a small displacement in the immediate pieces at the either side of the crack, which in turn causes a permanent shift in tilt (or inclination) of prestressed concrete. Such change in tilt is detected by fixed SenSpot sensors. Upon detecting a change in tilt, mobile robots will be dispatched to the location for a more thorough visual inspection. Such inspection will be directed by interactive commands from the human operator of the remote monitoring system