A Potential Field for Steel Bridge Inspection Climbing Robot

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***Abstract*— This paper presents a potential model for autonomous point-to-point locomotion of a climbing bicycle-like robot for inspecting ferromagnetic structures [1]. Previously, the robot has been human-controlled via an RC controller. This limits the range of the robot, as mobility is difficult when the robot is out of view of the user. An autonomous control framework allows for navigation across an entire structure without the need for user visibility. As the robot is restricted to navigation in two dimensions, the focus of this problem is to implement two dimensional navigation in a three dimensional environment. To solve this problem, two dimensional navigation is performed on a surface with an additional algorithm for handling plane-to-plane navigation.**

I. Introduction

Bridge inspections are essential to the nation with many aging infrastructures. In the United States, more than 618,456 bridges span the nation, and 45,031 are in poor condition [2]. Inspecting bridges is a dangerous and tedious task for humans. The standard practice to inspect steel bridges is hanging hundreds of feet by cables. People must manually inspect the bridges by sight or touching the areas of concern. There are potential hazardous variables that can arise with inspecting the bridge manually. Wind, rain, and heat are a few that could cause human error when inspecting the bridge.

A Climbing Robot (CR) that can traverse the entire bridge or just a section the engineer needs to inspect can allow safer measures for people. With many aging bridges, inspections need to be performed proficiently. Bridge inspections in the past have been insufficient, and devastating catastrophes have occurred. The State of Alabama nearly avoided a deadly catastrophic event when an inspector failed to see the crack in the bridge [4]. Fortunately, there were no deaths because the crack was found in time. The cost of shutting down the highway system to repair the bridge was an astronomical financial hit to the trucking industry and many other corporations. The inconvenience of the bridge closing was minor compared to the bridge collapse in Minnesota in 2007, where 13 people died, and 127 were injured [5].

Fig. 1. Dangerous bridge inspections taking place. [3]

There have been Climbing Robots to inspect steel bridges; however, they have been controlled by a low-level remote control and are massive compared to the current CR [6]. Transitioning a robot to motion planning will allow for safer and more in-depth inspections of bridges, unlike the predecessors. One CR uses four Omni wheels and can go in any direction without rotating the robot. Allowing the robot to have four Omni wheels does not require a turning radius. The CR was created with high magnetic force and uses a ground control station to receive data and control the CR [7]. Some robots use software and cameras to detect bridges' cracks, rust, and other possible defects. The predecessor of the CR that we are implementing the motion planning for is similar, except it has a few extra hinges that give the CR a few more degrees of freedom [1].

Transitioning the CR from remote control to a point-

This work is supported by the U.S. National Science Foundation (NSF) under grants NSF-CAREER: IIS-2150394, NSF-PFI-TT: 1919127, the NSF-REU: 115-2150394, and the U.S. Department of Transportation, Office of the Assistant Secretary for Research and Technology (USDOT/OST-R) under Grant No. 69A3551747126 through INSPIRE University Transportation Center (http://inspire-utc.mst.edu) at Missouri University of Science and Technology. The views, opinions, findings and conclusions reflected in this publication are solely those of the authors and do not represent the official policy or position of the NSF and the USDOT/OST-R.

Travis Page, Odyssey Engineering bridge mapping.

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Fig. 2. A bridge inspector is hanging dangerously to analyze and check for any defects on the Golden Gate bridge. [8]

to-point motion plan will improve the safety and lives of people inspecting and using the bridges. The engineer will need to survey the bridge with LIDAR to produce a 3D map of the bridge. Once the engineer has the bridge map, they can upload the image into a CR and give the location on the bridge that needs to be inspected while staying safe and secure on the ground.

Range and visibility are advantages of using motion planning over the remote control. When using the remote control, the robot does not know to inspect all areas on the way to the chosen location. Instead, the CR only inspects where the engineer says to inspect. Implementing point-to-point motion planning will force the CR to inspect the bridge entirely while moving to the chosen location.

Another reason motion planning is superior to the remote control is the range. Because the steel bridge may be too large, and the engineer may lose communication with the CR using a remote control. Losing communication with the CR could cause it to be left in place until someone can retrieve it. If an unfortunate incident took place, not only is the CR grounded, but the inspection is now on hold, and any critical areas are not being seen. If the CR was grounded, there could also be catastrophic consequences.

Implementing motion planning for the bicycle like CR will allow many improvements to the current remote-control-based Climbing Robot. The CR will allow more complex steel structures to be inspected, repaired, and kept safe for use. The current number of poor bridges in the United States would decrease due to efficiency and safety. Improving the CR from remote control to motion planning will advance the field of bridge inspection robots and improve upon the already existing technologies to advance civilization.

II. **Literature Review**

Steel structure Climbing Robots are new to the bridge inspection field. With each new design implemented, better methods are engineered to improve upon the last design. If the bot was not improved upon by the latest design, it was modified to a different design for structural inspection purposes. Some bots can be improved, while others need a more complex architecture to inspect a complex steel structure or bridge.

Several of the previous robots have addressed one area of concern or another. The functionality of the robot is dependent upon the design and model. Each model brings with it a new set of skills to further the advancement of the field. A previous magnetic CR has an extreme force to adhere to steel structures but does not traverse small areas well [9]. One hybrid model was engineered to combine flying and climbing for inspections [3]. The hybrid model is controlled by remote control and is not autonomous; because of the limited range, the robot's efficiency decreases.

Previous projects for path planning have looked into the RRT and RRT* algorithms for path planning in a 2D model [10]. The previous path planning expanded to all nodes and found the quickest route to the target point. This approach sometimes uses more than one robot to graph the path. Drone path planning can use repulsive and attractive forces to allow the drone to create its path plan [11]. By using potential fields for drones, the drones can avoid collisions with repulsive force and make it to their target with an attractive force.

There has also been deck detection on some of the previous robots. The deck inspection uses ground-penetrating radar to inspect the surface and interior of the bridge [12]. A few robots detect the aging rebar inside the concrete on bridges. One option is to use SH-waveform tomography to detect the delamination and rebar debonding [13]. Another possibility of checking the health and maintenance is to use Ground Penetrating Radar sensors. With this technology, they created an automated rebar detection system using Deep Residual Networks [14].

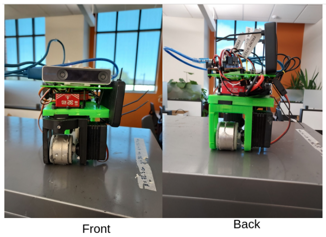

Fig. 3. Climbing Robot for steel bridge inspections.

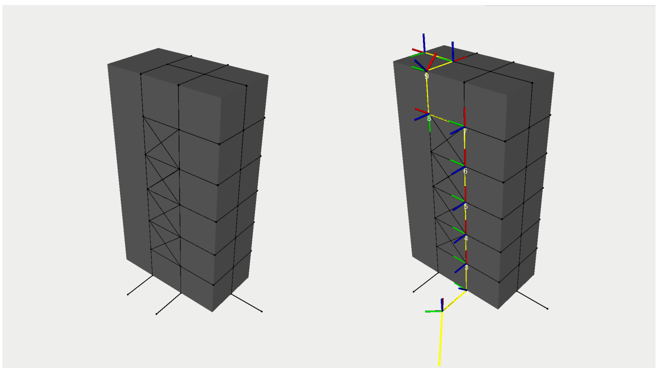

Fig. 4. Visualization of the graph model in RVIZ (left). Visualization of the path model in RVIZ (right)

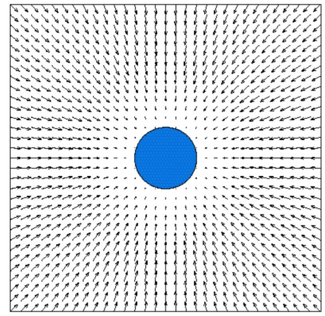

Fig. 5. An example of an attractive potential field.

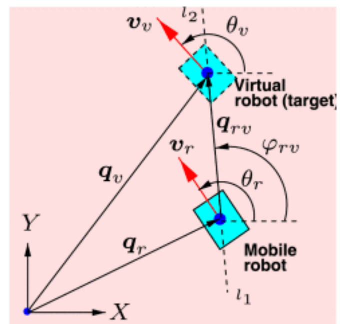

Fig. 6. A diagram of the kinematic model for the potential field

III. Robot Navigation and Motion Control

The core goal of this project is to design a model for three-dimensional autonomous point-to-point navigation. However, as this robot is limited to navigation on the surface of a structure, it is not truly capable of free navigation in three dimensions. However, two-dimensional navigation is traversing on the plane of the surface.

A. Path Finding

A CAD model is used for the structure to address this issue; a graph of vertices is defined in a uniform distribution on the structure's surface. The relative translation defines edges of the graph from the source vertice to the target vertice and the relative rotation from the source to the target. Figure [4] (right) shows a visualization of the graph model.

By using this graph, a path navigable by the robot can be created. The best-path algorithm A* was used to find the shortest path between the starting location of the robot and the target location. Figure [4] (right) shows a visualization of the generated path, including the expected position and orientation of the robot at each path point.

B. Artificial Potential Field

Two-dimensional motion planning can be performed with the path of waypoints defined. We achieve this by using an artificial potential field method, in which a vector field is defined with all vectors oriented in the direction of the target and have a magnitude relative to the distance from the target. Figure [5] shows an example of an attractive potential field.

Following is the kinematic model used to simulate the potential field for two-dimensional motion [15] 6.

$$q_{rv} = q_v - q_r \tag{1}$$

Equation 1 for the distance vector between the robot and the waypoint.

$$\varphi_{rv} = \arctan 2(y_{rv}, x_{rv}) \tag{2}$$

Equation 2 for the angle between the robot and the waypoint.

$$V_r^d = \sqrt{\|p\|^2 + 2\lambda\|q_{rv}\|\|p_v\||cos(\theta_v - \varphi)| + \lambda^2\|q_{rv}\|^2} \tag{3}$$

Equation 3 for the desired velocity of the robot, where λ is a small constant.

$$\theta_r^d = \varphi + \sin^{-1} \frac{\|p_v\| \sin(\theta_v - \varphi)}{\|p_r\|} \tag{4}$$

Equation 4 for the desired orientation of the robot.

As the target is a static waypoint, these equations can be modified assuming the target has a velocity of zero:

$$v_r^d = \sqrt{\lambda^2 \|q_{rv}\|^2} \tag{5}$$

$$\theta_r^d = \varphi \tag{6}$$

To determine the relative angle the robot must turn to reach the desired orientation, the difference between the current robot orientation and the angle between the robot and the target can be found.

$$\Delta\theta = \varphi - \theta_r \tag{7}$$

C. A* Algorithm

IV. Analysis

The first phase in our point-to-point locomotion navigation was a simulation done in RVIZ. The simulation uses a modified A* algorithm with edge detection to traverse the sides of the structure. Using A* allowed us to see how the closest path function worked in the simulation. One issue arose when a gimble lock continued to become present in the testing. To address the issue, we used quaternion angles with the TF ROS library, which allowed us to correct and improve the code to proceed forward. Several successful trials helped validate that the methods were working and that we could proceed to the next phase.

A GUI was implemented to control the target position of the CR by just adding in the coordinates. Implementing the GUI will allow a user to control the bot easily without knowing how to run ROS. The GUI makes the target point for the potential path planning far more user-friendly and comprehensive.

The second testing phase moved us from simulation to testing on physical objects. We first tested on a file cabinet using RVIZ to show the path in real-time of the CR. After noticing the odometry reading was off, we had to collaborate and find a better method. After understanding that the Realsense T265 needed a visual orientation, we decided to mount the camera slightly pointed up. Next, we repositioned the mounting of the Realsense T265 backward by a few inches.

The point-to-point algorithm performed well. When approaching another plane other than the one the CR was currently on, the robot had no issues maneuvering the surface change. The plane transfers needed to be completed with a 90-degree angle by the CR. The CR had no complications performing the 90-degree angle requirement surface change. The 90-degree angle change was a prerequisite for the plane change to ensure the robot had complete contact with the surfaces.

Next, we mapped the makeshift bridge in our environment using Dot 3D. Dot 3D worked reasonably well. The following approach we tested was with Meshroom, where we recorded the makeshift bridge. After the video, we added a python script to break up the frames.

Algorithm 1: A*

```
Input: verticeGraph, startNode, targetNode
Output: path
for node in verticeGraph do
    nodeScore = infinity;
    node.heuristic = infinity;
    node.visited = false;
startNode.score = 0
startNode.heuristic = 0
calcHeuristic(nextNode, targetNode)
        p1 = nextNode
        p2 = goalNode
        distance = p2.x^2 + p2.y^2 + p2.z^2
        return distance
while true do
    currentNode =
      nodeLowestScore(verticeGraph)
    currentNode.visited = true
    for nextNode in currentNode.negihbors do
        if nextNode.visited == false then
            newScore =
              calculateScore(currentNode,
              nextNode)
            if newScore < nextNode.score then
                nextNode.score = nextNode.score
                  = newScore +
                  calcHeuristic(nextNode,
                  targetNode)
                  nextNode.routeBack =
                  currentNode
                if currentNode == targetNode
                  then
                    return
                      pathFound(targetNode)
```

Once our video was broken into frames, we rendered a 3D image with Meshroom. To add vertices to the makeshift bridge, we took the .dwg file and entered it into solid works.

After mapping the bridge using a measurement gun and GPS with land surveying equipment, we obtained a 3D map made through AutoCAD [16]. After obtaining the 3D map, we can add vertices to the bridge for the CR to follow with its potential path planning. We will be addressing how to dynamically place the vertices in future work, but currently, it is a manual placement of the vertices of the graph on the bridge.

The simulation produced the best results because the environment was controlled. The file cabinet generated almost the same results as the simulation, with a slight variation in the odometry reading, making the bot slightly deficient in getting to his target. Both structures had the exact dimensions, but the simulation was superior due to its controlled environment.

For testing purposes, a teleop was implemented to control the robot. The implementation of the teleop allowed the CR to traverse plane to plane without the navigation software, which allowed for design testing flaws. One design flaw addressed is the tread on the neodymium magnetic wheels. The 3D-printed treads we had created allowed the robot to tip over because they were too bulky and the center of gravity was too high. When the treads were taken off the CR, the magnetic force was too great to release from the surface the robot left to the surface he had just engaged.

The teleop advised us how the potential field should take a 90-degree angle to ensure it did not tip over. By implementing the teleop, we could save time on testing specific areas of concern while eliminating the possibility that the potential field was not working correctly. During the testing phase, the CR would climb or traverse the steel structures, easily maneuvering any obstacles.

-Add in more automation

V. Results

In conclusion, our research for the Climbing Robot will ultimately replace humans in this work area. The goal of replacing humans with robots is not to displace human workers but to allow them to stay safely on the ground and inspect through a handheld device. Allowing the CRs to do the dangerous work will help improve many people's lives. The advancement in autonomous bridge inspections will only allow the world's aging bridge infrastructure to be repaired in a timely fashion.

The good-rated bridges in the US are only 45 percent in all. We have more bridges in the fair and poor category than the good. These numbers are also from a human inspection, so they could be much higher than reported. With the CR, the goal is to find and fix as many bridges as possible before they fall into fair or poor condition. More bridges can be inspected without worrying about the safety of humans; because of this, we can inspect a more significant number of bridges annually. Robots do not need to worry if the weather outside is good or if the bridge is too hot or too cold. These calculations still become present in measuring the bridge's health, just not if the robot can be deployed.

VI. Future Work

Our research will continue for CR ferromagnetic structures. We will design a tank like CR with magnetic treads. The tank-like CR will use differential steering and have tension tighteners to allow it to traverse the different types of structures the robot may encounter. Differential steering and tank treads will allow for more surface coverage when transitioning from one plane to another; this should also help with the magnetic force the wheels experience when leaving a plane.

We will add a lidar sensor, depth camera, and position camera for future mapping. The goal of using all three in conjunction with each other is to have a localized onboard mapping system. An onboard mapping system will allow the CR to go to work mapping the environment and inspect it all in one occurrence.

The implemented GUI will be redesigned to work with a touch screen. Adding a touch screen will allow the user a more effortless experience in working with and directing the robot. The touch screen GUI will allow for the mapping the CR does to be loaded and used right away. Once the map is loaded, the inspector can touch the area of the bridge the inspector wants to be inspected.

With the new design in the future, we expect a more robust Climbing Robot with almost all features onboard. The differential steering and tank-like treads will allow the CR to take many angles other than only a 90-degree turn. Having the tank-like treads will also prevent tipping over. The user-friendly GUI will allow many people with different backgrounds and skill sets to command the robot.

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