Enhancing the Locomotion of an In Vivo Robot for Cardiac Surgery

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***Abstract*— This paper describes a technique to improve the locomotion of a miniature crawling robot, (HeartLander) that uses suction to adhere to the surface of the beating heart. During locomotion, maintaining a vacuum seal with at least one of the suction pads is crucial. A new algorithm was developed to analyze data from pressure sensors monitoring the suction pads to accurately determine the suction status. HeartLander demonstrated successful locomotion on a realistic beating heart model when the algorithm was implemented.**

I. INTRODUCTION

Minimally invasive surgery is a revolutionary method in the world of surgery, but is difficult on the beating heart because of access limitations and the need for mechanical stabilization and lung deflation. The robotic system currently used in minimally invasive cardiac surgery is the da Vinci system (Intuitive Surg., Sunnyvale, Ca., USA). Although this robot provides improved dexterity and visualization, the inability to reach remote workspaces, such as the posterior wall of the left ventricle, the need for mechanical stabilization and lung deflation, and the cost of the robotic system continue to be problematic. Thus, in situations where compact size and efficiency are critical, a structure with minimal weight and complexity is preferred. One solution that has been presented to address the aforementioned limitations of cardiac surgical robotics uses a miniature crawling robot, HeartLander [1,2]. This miniature bipedal robot does not require lung deflation for access to the heart because it can be inserted through a small incision in the pericardial sac and crawl to any desired point on the surface of a beating heart. Additionally, this methodology facilitates surgery on the beating heart without requiring compensation of heartbeat motion.

II. LOCOMOTION

Locomotion of the HeartLander is a cyclic process that involves coordination between the wire actuation and the suction pressure status (Fig. 1). This section describes the details of the forward locomotion cycle and the potential problem that can hinder advancement.

A. Forward Locomotion

For the forward locomotion cycle of the HeartLander, the robot starts with both of the suction pads having a good grip of the epicardium (the outer surface of the heart). When the surgeon moves the joystick forward (commanding the robot to move forward), the vacuum of the front foot is turned off and the wires are advanced to extend the front body while the rear foot maintains its suction. After elongation, the vacuum of the front foot is turned back on and the robot anchors its front foot on the walking surface. Once the front foot is engaged, the vacuum of the rear foot is turned off; and the wires are pulled to retract the rear body to the front body and contact the walking surface. Then it will try to get a good grip of epicardium. This inchworm-like procedure will be repeated to walk along a straight line. If the robot needs to steer its direction, the lengths of wires will change depending on the direction of the turn (Fig. 1).

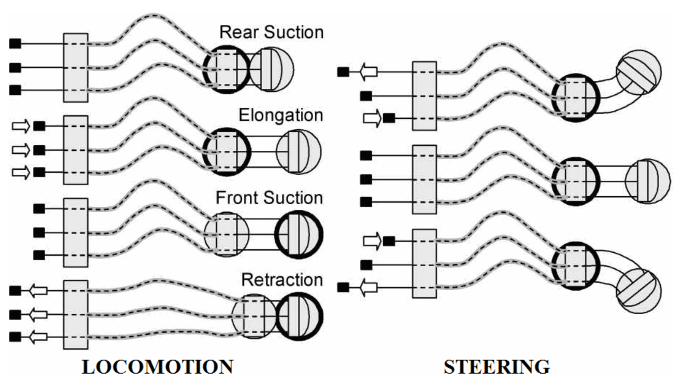


Fig. 1. Illustration of locomotion of HeartLander.

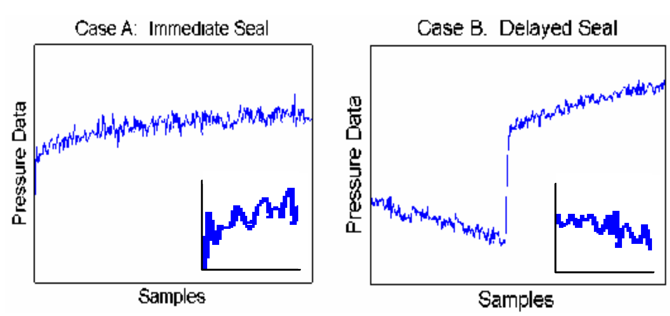


Fig. 2. Illustration of case A and case B. Insets show first 1 second of data.

B. Potential Problem

The most critical part of the locomotion cycle occurs after elongation and retraction; when the vacuum on the moving body is turned on and the robot tries to find a suction seal. Failure to ensure a proper seal will result in loss of adhesion to the heart during the next step. Therefore, compensatory motions are made to try to get the seal when the moving foot has no seal. Due to the movement of the beating heart and its curved surface, finding a good grip of the epicardium after releasing contact is nontrivial. Therefore, it is critical to determine the suction status quickly to avoid performing compensatory motions that might actually knock the robot off the surface.

To obtain further details about the abovementioned problem, we collected pressure data from each foot and observed the different suction conditions. We classified the possible suction states into three cases (A, B, and C). In the first case, the moving foot gets a good grasp of the epicardium immediately after the vacuum is turned (case A). As shown in Fig. 2, pressure data keeps increasing until it plateaus. On the other hand, if the moving pad never gets a good grip of the epicardium, the robot cannot proceed (case C). The plot for this case the opposite of case A, where the pressure decreases until it plateaus. Alternatively, if the front foot gets sealed shortly after the vacuum is turned on, then it is case B. As it can be seen from the graph of pressure data for case B, the pressure readings decreases for a while, then jumps sharply upon getting a seal and continues to increase until it plateaus. Thus, case B is a combination of cases A and C, starting with case C, then transitioning to case A. During case B, it is crucial to determine whether or not a the moving foot has gained a seal with the surface in order for the robot to take the appropriate action.

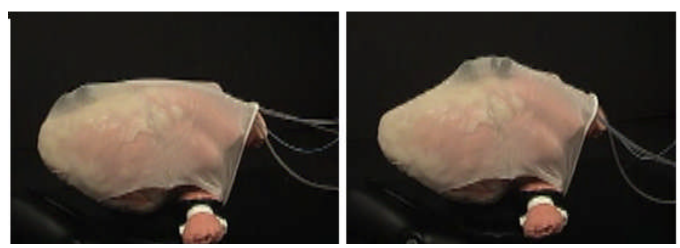
III. SOLUTION

In order to approach this problem, we first distinguished between cases A and the set of cases [B, C], then further differentiated between cases B and C. This is because initially cases B and C are similar, both decreasing, whereas case A increases from the beginning. While collecting pressure data from each foot, we approximated the slope of the pressure data. This was accomplished by implementing linear regression over a sliding window in the existing locomotion software. The slope data showed us the first derivative calculated over a certain window length to avoid noise in data. We examined the first value after switching on the vacuum to the moving foot to figure out the minimum window length over which distinguishing between cases A and [B, C] was possible. A negative value of the slope of the pressure data indicated that the foot did not have suction seal; therefore the pressure data graph was decreasing and it was case [B, C]. On the other hand, a positive value indicated that it had suction seal; thus it was case A. For all three cases, we collected 10 trials each for window lengths of 10, 20, 30, 40, and 50. We observed that window length of 20 was the minimum window length that yielded 100% accuracy in evaluating the first point following the vacuum switch; i.e. a positive value for every case A, and a negative value for cases B and C. We then evaluated window lengths of 13, 14, and 15 to determine the optimal window length with better resolution. A window length of 15 also yielded 100% accuracy, whereas window lengths of 14 and 13 yielded errors. As a result, 15 was the minimum window length to distinguish between cases A and [B, C].

To differentiate between cases B and C, we no longer looked at the first value since it would be a negative value for both cases. This time we wanted to detect the moment that it gets suction seal and causes the pressure data to increase rapidly (Fig. 2). We chose window lengths of 10, 20, 30, 40, and 50, and collected 5 trials of data. For the calculated slope data of case B, we require that the values of all data before the spike point to be negative, because that is when there is no suction seal and therefore the pressure decreases. Looking at the percent error of having positive values before spike point, a window length of 20 was the minimum length that gave us 0% error to distinguish between cases B and C.

IV. CONCLUSION AND TESTING

In conclusion we determined that a window length of 15 was the optimal window length to differentiate between cases A and [B, C], and a second window length of 20 was the optimal widow length to further differentiate between cases B and C. In order to verify our results, we tested the HeartLander with and without the new suction detection algorithm on a realistic beating heart model with a nylon pericardium (the sac that encloses the heart). The robot demonstrated successful locomotion across the curved surface of the beating heart model with the new suction detection algorithm, whereas it failed when the algorithm was deactivated (Fig. 3).



(a) (b)

Fig. 3. Photographs of the HeartLander during the locomotion test: (a) successful walk with the suction detection algorithm active , (b) failure to reach to goal point without suction detection.

REFERENCES

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