Proceedings of the 2005 IEEE
Engineering in Medicine and Biology 27th Annual Conference
Shanghai, China, September 1-4, 2005

A Miniature Cable-Driven Robot for Crawling on the Heart

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Abstract—**This document describes the design and preliminary testing of a cable-driven robot for the purpose of traveling on the surface of the beating heart to administer therapy. This methodology obviates mechanical stabilization and lung deflation, which are typically required during minimally invasive cardiac surgery. Previous versions of the robot have been remotely actuated through push-pull wires, while visual feedback was provided by fiber optic transmission. Although these early models were able to perform locomotion in vivo on porcine hearts, the stiffness of the wire-driven transmission and fiber optic camera limited the mobility of the robots. The new prototype described in this document is actuated by two antagonistic cable pairs, and contains a color CCD camera located in the front section of the device. These modifications have resulted in superior mobility and visual feedback. The cable-driven prototype has successfully demonstrated prehension, locomotion, and tissue dye injection during in vitro testing with a poultry model.**

I. Introduction

A large percentage of cardiac surgeries are now being performed in a minimally invasive manner to avoid the morbidities associated with traditional, open procedures [1]. The use of robotic devices to assist with these procedures is also becoming more prevalent due to the improvements in dexterity and visualization that can be provided in the confined environment of minimally invasive surgery [2]. HeartLander differs from conventional surgical robotics in that it adheres to the organ on which it performs intervention, and has the ability to travel on this organ (Fig. 1). With regards to cardiac intervention, this paradigm obviates the need to mechanically stabilize the epicardial surface in order to administer therapy on the beating heart [3], [4]. The locomotive capability of the robot improves access and allows a less invasive approach for insertion of the robot onto the heart surface [5].

Congestive heart failure caused by myocardial infarction is the leading cause of death in the industrialized world [6]. Because cardiomyocytes are terminally differentiated, there are currently no effective means to replace scarred myocardium with viable functioning myocardium. The injection of stem cells (precursor cells capable of differentiation into cardiomyocytes) into failing myocardium offers the potential to reverse the deleterious effects of myocardial infarction that lead to congestive heart failure [6]. The results of preclinical animal studies and early clinical investigations have shown regenerated myocardium and increased perfusion in the infarct area leading to improved cardiac function [7],[8],[9]. As testing of stem cell injection matures, enhanced delivery methods that provide superior access in a less invasive manner will become essential.

In prior work, we designed and tested two wire-driven HeartLander prototypes *in vivo* on beating porcine hearts [10]. The first prototype successfully demonstrated prehension and locomotion on the beating heart with the pericardium (the sac enclosing the heart) removed [11]. The major improvements made to the second wire-driven prototype were the reduction in size and the addition of a needle injection system. These modifications allowed the second prototype to navigate and perform tissue dye injections on the heart surface with the pericardium intact [12]. Despite these successful preliminary tests, the tether required for wire-driven actuation and fiber optic visual feedback limited the mobility of the robot during turning and walking around the posterior side of the heart.

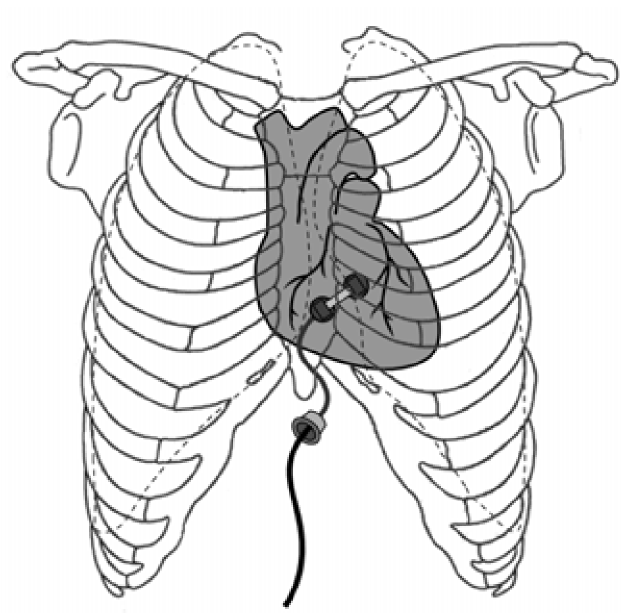

Fig. 1. An illustration of the HeartLander concept, where the skin, ribs, and connective tissue are depicted as transparent for better visualization of the robot. The robot enters the thoracic cavity through a small port below the sternum, adheres to the surface of the heart using suction, and travels to any location to administer therapy under the direct control of a physician.

Manuscript received May 2, 2005. This work was supported by the National Science Foundation (grant no. EEC-9731748).

II. DESIGN

Once placed on the surface of the heart, HeartLander must be able to reach any arbitrary location for treatment. The robot is inserted onto the epicardium (heart surface) through an endoscopic device introduced into the thoracic cavity through a 10-mm incision below the sternum (Fig. 1). This endoscopic device is able to passively cut the pericardium, providing direct access to the underlying epicardium [13]. HeartLander adheres to the epicardium using front and rear suction pads that are supplied vacuum pressure from external pumps through vacuum lines in the tether. The physician directly controls the robot with a joystick interface, while receiving visual feedback from the front of the robot.

A. Locomotion

The new cable-driven HeartLander has two active degrees of freedom and one passive degree of freedom. The active degrees of freedom are actuated by two sets of antagonistic cable pairs. One cable pair provides rotation of the rear body relative to the suction pad on which it sits, which allows turning. The other cable pair controls the translation of a prismatic joint connecting the rear and front body sections, allowing the robot to extend and retract. Stainless steel 3x7 braided cable with a diameter of 0.23 mm is used in both cable pairs. Sheathing to maintain tension in the cables is provided by small plastic tubing. The passive degree of freedom is provided by a flexible connection between the prismatic joint and the front body section. This allows the front body to pitch in order to passively adapt to the curvature and motion of the epicardial surface.

Inchworm-like locomotion is accomplished through coordination between the motors controlling the two cable pairs and the solenoid valves that regulate the vacuum pressure in the front and rear suction pads. To step forward, the following set of internal commands are executed:

1) rear suction = ON, front suction = OFF,
2) body length = EXTEND,
3) front suction = ON, rear suction = OFF,
4) body length = RETRACT.

To step backward, commands 1 and 3 are simply reversed. This internal coordination is maintained by the software, and is thus transparent to the physician. A joystick provides a simple manner with which to administer the following four commands: *rotate right*, *rotate left*, *walk forward*, and *walk backward*. The turning and locomotion speed can also be adjusted from the joystick, allowing fine position control in sensitive situations. Throughout the locomotive cycle, the software monitors the readings from external pressure sensors attached to the vacuum lines to ensure that at least one suction pad maintains a grip on the heart surface at all times.

B. Visual Feedback

During locomotion and treatment, visual feedback from the front body section is provided by a 3.5-mm diameter color

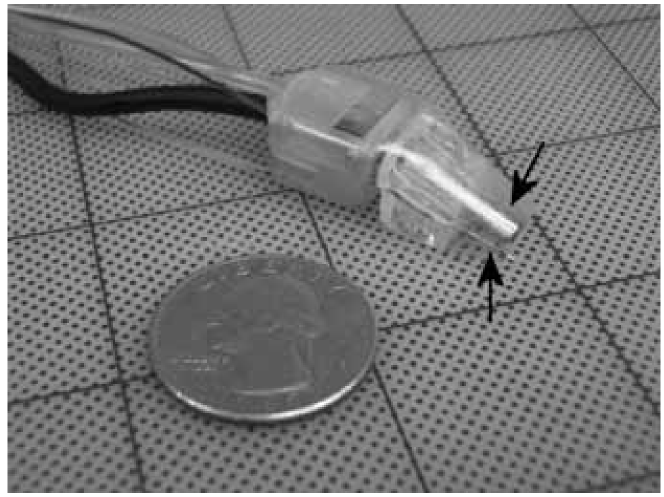

Fig. 2. The cable-driven HeartLander prototype (U.S. quarter shown for scale). The upper arrow highlights the 3.5-mm diameter CCD camera through the translucent tapered front body, while the lower arrow highlights the needle. The height of the robot is 10 mm and the length is 30 mm.

Fig. 3. View of a steel ruler through the CCD camera located in the front section of the cable-driven prototype. The tick marks on the left side indicate millimeters; all lines are approximately 0.25-mm thick. The extended needle for tissue injection can be seen in the lower-right corner.

CCD camera (Fort Imaging Systems, France). The resolution of this camera is 537(H) x 597(V), which is sufficient for recognition of epicardial landmarks for both navigation and administration of therapy. The depth of field is 5-mm to infinity and the field of view is 90 degrees, allowing visualization of the needle tip during puncture and injection (Fig. 3). Lighting is provided by two sets of flexible incoherent fiber optic bundles.

C. Needle Injection Method

A flexible needle injection system was developed to allow injections to be performed by hand through the HeartLander tether without increasing the stiffness. A 12-mm long 27G needle is located in a channel through the front body section that is slanted 20 degrees toward the epicardial surface. The proximal end of the needle is connected to flexible plastic tubing that supplies the injection material into the lumen of the needle. This tubing is advanced through an outer sheath at the proximal end of the tether in order to advance the needle out of the channel into the tissue. The needle is retracted into the channel by pulling back on the inner tubing. This transmission method is analogous to that of a push-pull wire transmission, where the inner tubing acts as the wire. Visual feedback from the camera system, along with minimal tactile feedback from the proximal portion of the inner sheath, allow the physician to determine the depth of the needle puncture.

III. TESTING

The cable-driven HeartLander prototype was bench tested using a poultry tissue model. The robot was able to travel across the surface of the tissue without restriction from the tether (Fig. 4). Turning up to 90 degrees was successfully demonstrated. Tissue dye injections were also performed in several locations following locomotion (Fig. 4, 5). The visual feedback from the color CCD camera was sufficient to accurately determine the location and the depth of the needle puncture prior to injection.

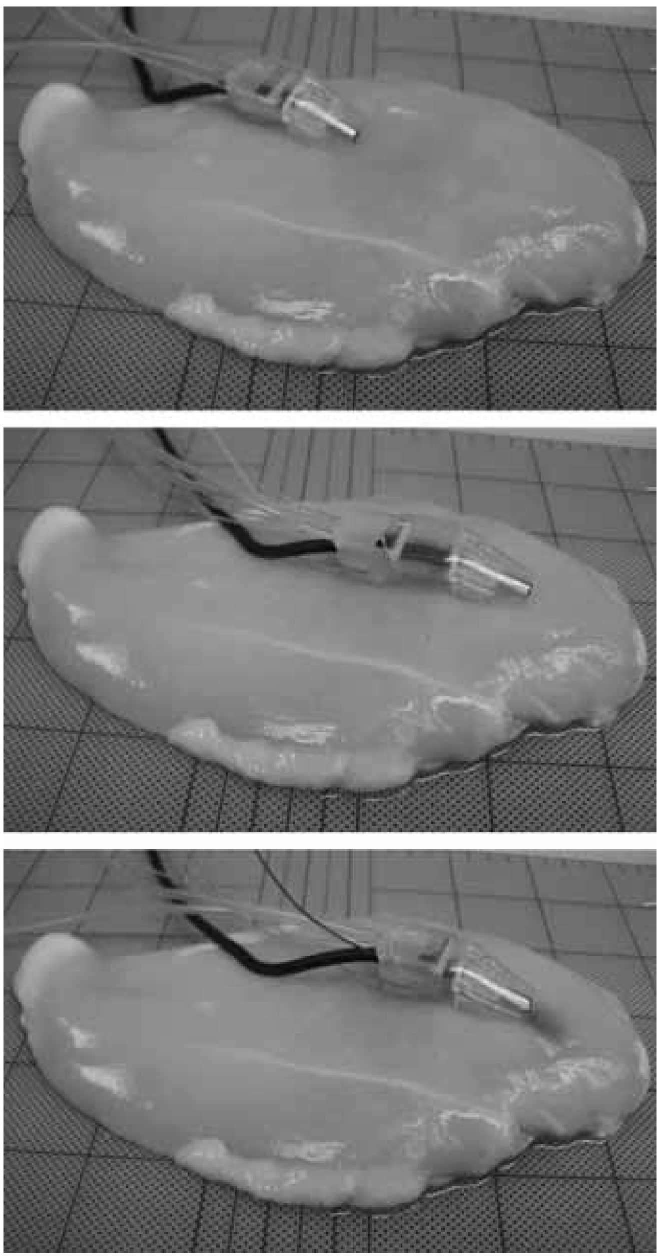

Fig. 4. A time series of photographs showing the cable-driven HeartLander robot walking across the surface of poultry tissue and performing an injection of ink into the tissue.

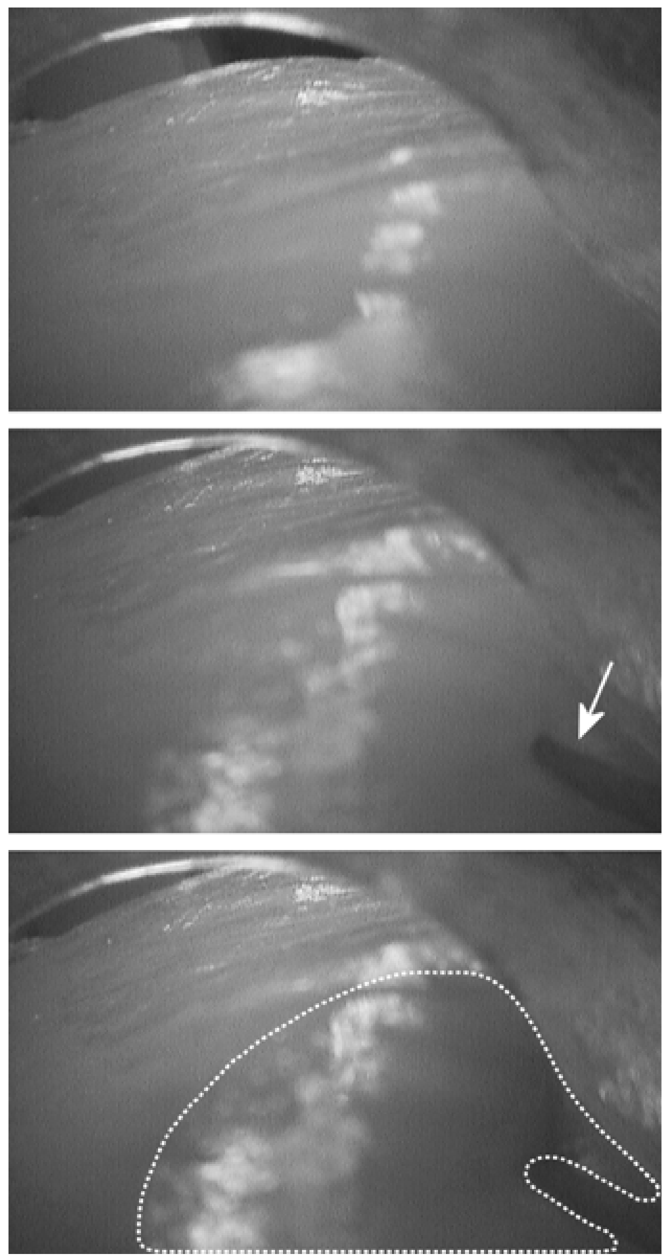

Fig. 5. A time series of images taken through the CCD video camera during a dye injection into poultry tissue. *(middle)* The needle (highlighted by the arrow) has punctured the tissue. *(bottom)* The injection has been performed (the dyed tissue is highlighted by the dotted border).

IV. Discussion

These tests demonstrate the ability of the cable-driven HeartLander prototype to adhere to muscular tissue, travel along both straight and curved trajectories, and perform tissue dye injections under visual feedback. Both navigation and dye injection were facilitated by the vastly improved quality of the visual feedback from the CCD video camera.

The increased flexibility of the tether resulting from the use of cables instead of push-pull wires will be quantified in future work. This enhancement should improve the mobility of the robot during the next series of tests that will be performed *in vivo* on a beating pig heart with the pericardium left intact. The 10-mm height, tapered front end, and shielding between the front and rear body sections will also assist toward this goal. Testing will eventually proceed to the delivery of needle-based therapy through a totally minimally invasive approach.

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