Project Title: MARS: Maryland Autonomous Robotic Surgeon

Team: MRE (Medical Robotics and Equipment) Lab

Team Lead: Assistant Professor Dr. Axel Krieger

Team Members:

- Post-Doctoral Fellow Dr. Hamed Saeidi
- Graduate Student Michael Kim
- Graduate Student Jiawei Ge

Project Objective:

We propose to build and test a novel surgical robotic system, the Maryland Autonomous Robotic Surgeon (MARS), capable of automating the surgical procedure of appendectomy. MARS will be built upon the existing framework of the smart tissue autonomous robot (STAR), the first surgical robot capable of semiautonomous surgical tasks in soft tissue. To create MARS, our team will integrate a 3D sensor capable of reconstructing the surgical field, design a new surgical tool to access the abdominal cavity, develop an imaging algorithm to detect an inflamed appendix, and automate stapling and cutting of the appendix. The project consists of the following four objectives:

1) Locate abdomen, find entry points for tools and camera, and insert into the body.
2) Identify and isolate the inflamed appendix.
3) Stabilize and remove the inflamed appendix.
4) Remove tools and camera and close the skin.

At the end of the 12 months project, we will execute these four objectives to demonstrate autonomous appendectomy in a phantom model. This project will represent the first complete autonomous robotic surgery. This robot has the potential to reduce complications of manual surgery and enable exploration of new frontiers without the need for surgical support.

1 Goal and Objectives

We propose to build and test a novel surgical robotic system, the Maryland Autonomous Robotic Surgeon (MARS), capable of automating the surgical procedure of appendectomy. MARS will be built upon the existing framework of the smart tissue autonomous robot (STAR), the first surgical robot capable of semiautonomous surgical tasks in soft tissue. To create MARS, our team will integrate a 3D sensor capable of reconstructing the surgical field, design a new surgical tool to access the abdominal cavity, develop an imaging algorithm to detect an inflamed appendix, and automate stapling and cutting of the appendix. The project consists of the following four objectives: 1) Locate abdomen, find entry points for tools and camera, and insert into the body. 2) Identify and isolate the inflamed appendix. 3) Stabilize and remove the inflamed appendix. 4) Remove tools and camera and close the skin. At the end of the 12 months project, we will execute these four objectives to demonstrate autonomous appendectomy in a tissue model. This project will represent the first complete autonomous robotic surgery. This robot has the potential to reduce complications of manual surgery and enable exploration of new frontiers without the need for surgical support.

2 Significance (Mpact)

Each year more than 300,000 patients develop acute appendicitis in the United States alone. The patient will present with an inflamed appendix that may cause abdominal pain, fever, nausea, and vomiting. If left untreated the inflamed appendix will eventually burst, spilling infectious material into the abdominal cavity. The spread of infection to the abdominal wall is life threatening if not immediately treated. The standard of care for these patients is to have their appendix surgically removed. While advances in laparoscopic surgery have enabled a minimally invasive approach to remove the appendix, the procedure is far from perfect. On average, 16% of patients will suffer a complication from the procedure that can be attributed to variations in surgeon skill, experience, training, and environment. An autonomous surgical robot could significantly reduce the number of complications. In manufacturing and transportation industries, the accuracy and precision of robotics consistently demonstrates the ability to perform repetitive tasks better than humans. Manually controlled tele-operated surgical robots have enabled minimally invasive keyhole surgery and reduced recovery time for patients, but have not decreased complication rates. A surgical robot that could autonomously identify and remove an appendix would benefit all patients requiring appendectomy, since robotic execution of best programmed techniques would permit improved standardization and access to best and safe surgical techniques. In addition to general hospital usage, an autonomous robot for appendectomy is critical to operations in isolated environments. There is global interest to enable exploration and deployment of personnel on long range space flights, polar explorations, and in submarines, where quick access to a trained surgeon is not readily available. The risk for acute appendicitis is sufficiently high, where personnel selected for these missions may be subject to prophylactic appendectomy, despite inherent mortality and morbidity. Utilizing current state-of-the-art telerobotic surgery for appendectomy is a possibility, but requires stable, fast, and high-bandwidth connectivity to a remote surgeon, which is not feasible for most missions.Instead, we propose isolated missions could be deployed with autonomous surgical robots capable of providing emergent medical support, where a surgeon is not available.

Beyond appendectomy, this technology is applicable to the millions of other surgeries performed every year. The successful completion of the proposed work will pave the way to a future where patients receive the best surgical treatments both at home and in remote locations independent of surgeon experience and training.

3 State of the Art

Advances in robotic and camera technology have led to dramatic improvements of medical robots. Robotic assisted surgery (RAS) systems, incorporate highly dexterous tools, hand tremor filtering, and motion scaling to enable a minimally invasive surgery (MIS) approach, reducing collateral damage and patient recovery times [16]. State of the art systems for robotic assisted surgeries are based on a tele-operated paradigm. The commercially successful da Vinci Surgical System (Intuitive Surgical, Sunnyvale, California) [8] is used for a wide range of surgical procedures in urology, gynecology, cardiothoracic, and general surgery. Another tele-operated system is the Raven surgical robot developed at the University of Washington [14].

The advantages of autonomous robotic functionality have been demonstrated in applications outside of medicine, ranging from manufacturing to self-driving cars [17], [18]. A limited form of autonomous RAS with pre-planned functionality was introduced in bony orthopedic procedures (e.g. ROBODOC, Caspar, and CRIGOS), radiotherapy, and cochlear implants [10, 6, 1]. Efforts in automating deformable and unstructured soft tissue surgeries have been limited so far to elemental tasks such as knot tying, needle insertion, and executing predefined motions [11, 15, 7, 12, 2, 5, 9].

In summary, current surgical robots are controlled directly by the surgeon with very little autonomy. This tele-operated control scheme limits medical robots, since dexterity, precision, and reproducibility are dependent on the capabilities and performance of the operating surgeon. Therefore, our goal is to perform complex surgical procedures with the highest possible degree of autonomy and to open new avenues for future medical robotic applications.

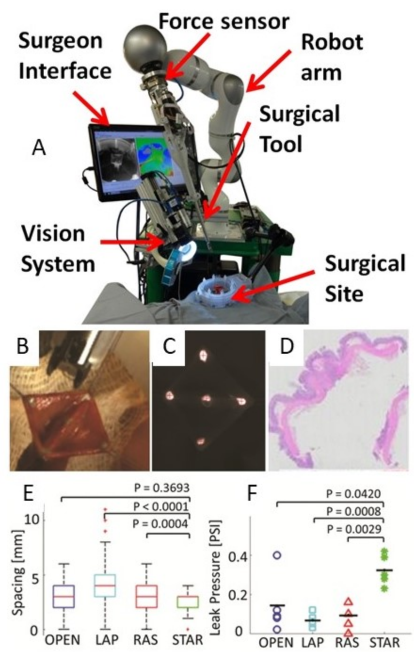

Fig. 1: Supervised autonomous anastomosis system and results. A: Picture of the STAR system with principle components. B: Staged bowel tissue, with NIRF markers, ready for suturing. C: NIR image of staged bowel showing tracked NIRF markers outlined in red. D: Histology slide showing good wound healing. E: Suture spacing results and F: Leak pressure results for STAR and compared modalities.

4 Prior Work

We developed STAR consisting of a KUKA LWR robot, a new robotic suturing tool, and custom control implemented using robot operating system (ROS) for GUI and camera integration, and open robot control software (OROCOS) for real-time control (Fig. 1A) [13]. An accuracy study of the STAR demonstrated a positional accuracy of 0.5 mm [13]. The STAR's vision system combines a plenoptic 3D camera (Raytrix, Germany), with a measured accuracy of 1 mm in surgical environments [3], with a near-infrared (NIR) camera. Combined with small near infrared fluorescent (NIRF) markers based on clinically approved Indocyanine green (ICG) and biocompatible cyanoacrylate (Permabond) the vision system enables accurate real-time 3D tracking of tools and target tissue while overcoming blood and tissue occlusion [4].

We successfully performed pre-clinical supervised autonomous robotic anastomosis of porcine small intestine using STAR. This study represents the first in vivo automated surgery on soft tissue (Fig. 1) [19]. We demonstrated in porcine cadaver experiments that STAR significantly improved the consistency in spacing (Fig. 1E) and burst pressure (Fig. 1F, $p = 0.008$) compared to manual and tele-robotic surgery.

5 Innovation

The proposed work represents the first complete autonomous robotic surgery. This work is based on key innovations in three areas: **1) Novel Tool Designs:** We will develop trocar access tools, robotic stapler, and closure tools that are optimized for robotic usage. **2) Imaging and Image Processing:** We will integrate 3D and Multispectral imaging to identify entry locations on the abdomen and to identify the inflamed appendix. **3) Autonomous Control:** We will develop and test custom image guided control for autonomous execution of the appendectomy procedure.

Abdomen Scanning and Trocar Placement Autonomous laparoscopic appendectomy requires an accurate 3D map of the patient's torso for entry port placement. We will equip our robot with a RGB-D camera (RealSense R200) that provides 3D position and color information of the torso (Fig. 2). Once a 3D point cloud map is created, a planning algorithm detects the belly button and size of the abdomen and generates the 3D location of trocars (Fig. 2.b), based on McBurney's triangle. Finally, autonomous port placement is performed by the robot using a needle with removable core.

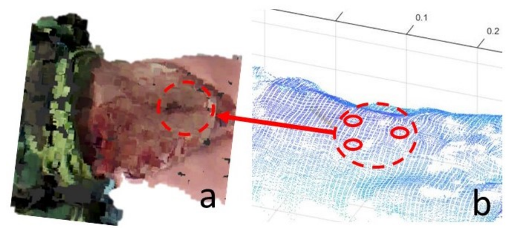

Fig. 2: a) RGB-D map collected by the robot for autonomous appendectomy, b) planned point/trocar placement.

Identification and Stabilization of Appendix After port placement, one robot with attached surgical forceps will be placed in the left lateral port and used to automonously grab the appendix. A second robotic arm with attached multispectral camera, will be placed through the caudal port and used to image the surgical field. The camera will autonomously identify and distinguish terminal Ileum, cecum, and appendix by measuring tissue reflectance at discrete wavelengths (470 nm to 760 nm). Parameters such as increased tissue densities, spectral reflectance due to the increased amount of blood plasma and leukocytes in the inflamed appendix, and spatial appearance are all used to automously identify tissues. The first robotic arm with surgical forceps will then use the camera information to locate, grasp, and stabilize the appexdix within the body.

Appendix Resection Once the appendix has been stabilized, a third robotic arm with attached laparoscopic stapler will be placed within the umbilicus port. Using the 3D coordinates found earlier, the stapler will be autonomously guided to the tissue and the tool jaws will be closed across the base of the appendix (Figure 3.a). After the tools jaws have closed, the appendix will be stapled and resected from the cecum (Figure 3.b). Mobilization of the lateral robotic arm will remove the appendix from the cecum stump. The appendix can then be removed from the body, by pulling it through the left lateral port (Figure 3.c).

Closure of the Abdomen After the appendix has been removed from the body, the robot will remove the camera and laparoscopic stapler, followed by port removal. The RGB-D camera will be used to reconstruct a second 3D map of the patient torso, and the three incision points of McBurney's triangle will be identified. A robotic arm with laparoscopic gluing tool will be autonomously commanded to each incision site. Surgical glue (Dermabond) will be topically applied to each incision site, closing the wounds. After closure, the RGB-D camera will be used to verify that all incisions have been properly closed.

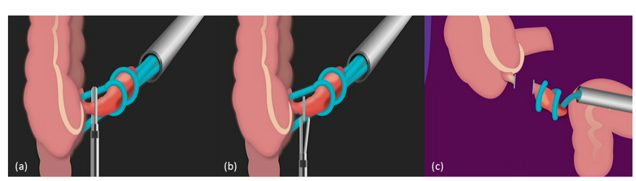

Fig. 3: a) Positioning the base of the appendix within the jaws of the laparoscopic stapler. b) Applying a staple line across the base of the appendix. c) Resecting the appendix from the cecum.

6 Project Plan, Metrics, and Milestones

For this project we will utilize our surgical robot, built on the STAR platform, consisting of two KUKA LWR robots, and a Universal Robotics UR5 robot for the camera on a height adjustable mobile cart. Testing will be performed on an educational appendix mannequin. The project will be devided and executed in four objectives: 1) Locate abdomen, find entry points for tools and camera, and insert into the body. 2) Identify and isolate the inflamed appendix. 3) Stabilize and remove the inflamed appendix. 4) Remove tools and camera and close the skin.

In objective one, we will integrate a new RGB-D camera with the robotic system that is capable of reconstructing a 3D point clouds, and design a new surgical tool that enables the robot to insert laparoscopic ports into a mennequins torso. Once integrated, we will conduct a 3D pointing test for accuracy where the robot will be autonomously controlled to user selected points on the 3D point cloud. Additionally the port insertion tool will be mechanically stressed to 10N to demonstrate it is robust enough for placement through the skin. Success for objective one is defined as the ability of the robot to corrrectly map the torso of the mannequin, identify three locations for port placement, and autonomously insert a port into each location.

For objective two, we will use our multispectral camera to identify the appendix and then use a robotic grasper to isolate the appendix from surrounding tissue. The multispectral camera will be used to measure the spectral profiles of liver, kidney, intestine, and inflamed appendix of our mannequin model. We will tune the detection algorithm to rebustly identify the appendix under different lighting conditions. Additionally, the laparoscopic grasper will be actuated and mechanically tested to verify it can push objects with 5N of force. Success for objective two is defined as the ability to detect the appendix, and the robot's ability to reliably grasp and isolate the appendix.

For objective three, we will use a robotic stapler to resect the appendix and then remove the appendix. We will mechanize a standard laparoscopic stapler and integrate with the robot. The stapler performs simultaneous cutting and sealing of the stump through the deployment of a double row of staples.Success of objective three is defined as the robot's ability to reliably staple and cut the appendix and then remove the appendix with the grasper through the trocar.

For objective 4, we will remove the laparoscopic ports, and autonomously close the port incisions with surgical glue. For this objective we will design a new robotic glue applier that is compatible with the surgical robot. The glue applier will undergo bench testing to demonstrate the ability to autonomously apply glue in spot and line patterns on phantom tissue. The tool accuracy will be measured using a 3D pointing task after integration with the RGB-D camera. Success for objective 4 is defined as the demonstrating a glue accuracy <1mm, and the ability to inject glue into three incision sites in a mannequin's torso.

Each objective will take 3 months to complete. At the end of the 12 month project, we will perform all four objectives simultaneously to autonomously resect an appendix from a mannequin torso phantom. Success of the project is defined as the design and construction of a new surgical robot that performs autonomous appendectomy.

7 Project Risks and Alternatives

There are risks that certain parts of the procedure proof more difficult to automate than expected and cause a slip in the schedule. In case of unexpected delays we will simplify procedures by allowing help of an on-site 'medic' to assist the robot with executing difficult to automate procedures, such as removal of the tools.

8 Budget

1. Materials and Supplies: $9,000 for stapler, mannequin, trocars, and supplies.
2. Post-Doctoral Fellow Hamed Saeidi (20%): $11,000
3. Graduate Research Assistants Michael Kam and Jiawei Ge (40% each): $26,600
4. Hourly Undergraduate (6hrs/week @$11/hr): $3400
5. Total: $50,000

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