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KidsArm – An Image-Guided Pediatric Anastomosis Robot

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Abstract— **Minimally invasive surgery (MIS) revolutionized surgery by drastically reducing patient recovery times by allowing surgeons to perform procedures through a series of small incisions. However, MIS has also increased the complexity of the tasks as tools did not have the same degrees of freedom and dexterity compared to open procedures. In particular, pediatric patients pose a unique challenge as they have smaller volumes and different tissue properties. Our group designed KidsArm, an image-guided pediatric surgical robot, to automate anastomosis. KidsArm is single port anastomosis tool that uses a pair of stereo cameras to generate a 3D point cloud to guide the tool tip and apply a series of sutures. The system was designed to be minimally invasive and constrained by standard pediatric trocar sizes while also being automated. An image processing system was created to extract and track surface features on the simulated tissue samples while providing feedback to the robot controller. The system was tested on two scenarios: side-to-side and end-to-end silicone samples. KidsArm successfully applied 3 sutures autonomously on the side-to-side scenario however the end-to-end scenario proved to be more difficult due to greater deformation and workspace restrictions. However, KidsArm demonstrates that it is feasible for a robot to autonomously perform anastomosis. More work will be required to accelerate the process and characterize the behavior with tissue samples.**

I. INTRODUCTION

Minimally invasive surgery (MIS) techniques revolutionized surgery and shorten patient recovery times by allowing surgeons to perform procedures through 3-4 incisions with a diameter up to 1-2 cm [1]. However, MIS procedures are often more challenging and complex as the surgeon is restricted to tools that do not possess the same flexibility as tools used in "open" procedures (done by hand through a large incision). Hence, there is a trade-off between the invasiveness vs patient recovery time. For pediatrics, the size and volume constraints are more pronounced as children have smaller organs, vessels and targets while the tools are the same or minimally smaller than adult versions. The small size and volume limits combined with a need for better tools to improve the speed and accuracy of the procedure make this a potential target for surgical robotics.

In this paper, anastomosis has been selected as the target task for robotic automation. Anastomosis is a general term used to describe the procedure of connecting two or more tissue or tubular vessels together [2]. There are 3 categories: end to end, end to side and side to side. Though conceptually simple, it is one of the most challenging tasks that can be found across all surgical specialties where for pediatric surgery it is much more difficult as the target vessels and tissue are smaller. When combined with the rigid and limited flexibility of current tools, the task becomes time consuming and complex. A survey of different techniques to speed up the suturing times range from 1-2 mins for automated instruments used in open procedure to 60 mins for manual open-based tools [3]. At the Hospital for Sick Children, the team has observed laparoscopic anastomosis that has taken up to 120 minutes. The use of MIS tools would only increase the duration.

Surgical robotics have increased in popularity as robots provided surgeons with added degrees of freedom and visualization that simplified and shorten certain types of tasks. For example, a comparison was conducted with robotic laparoscopy (RL) vs conventional laparoscopy (CL) which found there was a shorter learning curve for laparoscopic tasks and the execution time was shorter for tasks such as knot tying [4]. The dominant robotic system to date is the DaVinci System by Intuitive where it is a MIS 4 port surgical robot [5]. However, the majority of these systems operate under a master-slave environment where the robot is directly controller by the surgeon. Some group have explored using robotics as both assist and automated devices for MIS and cardiac surgery [6-7]. Due to safety and regulatory concerns, the concept of automated robotic surgery is still a relatively new area where some groups have explored stitch planning and virtual fixtures [8-9].

With advances in medical imaging and processing, groups have explored how to use intra-operative imaging (video, ultrasound, CT or MRI) to provide image guidance to the operator for better localization and targeting [10]. The features of image guidance and smaller dexterous tools could be the answer to providing better tools and improve patient outcomes. This paper describes the design and development of KidsArm, an image-guided robotic system that performs automated anastomosis under endoscopic video image guidance through a collaboration between Hospital for Sick Children and MDA.

II. DESIGN CONSIDERATIONS

KidsArm is designed to work on pediatric patients that primarily range from neonates to 4 years old. The age range creates a smaller volume restriction on the actual work space. Given the small size of the patients, the following requirements were specified:

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A. *Single Port Anastomosis Tool*

To minimize the need for additional incisions beyond the standard 3-4 used in MIS, a single port anastomosis tool was required. This meant that the anastomosis had to be deployed through a single standard trocar and perform the full connection task. Prior anastomosis tools have been developed but they often required the assistance of hands or other tools to place or orient the target sections.

B. *Trocar size limits*

The tool must fit within the standard pediatric trocar size of no more than 5 mm. This is done to prevent creating larger incisions.

C. *Target and operating volume limits*

The target sizes of the vessels are typically 5 mm in diameter, which are representative of vessels found within a pediatric abdominal region of a neonatal patient. The operating volume is defined as 2 cm x 2cm x 2cm space which matches the size of the pediatric abdomen.

D. *Anastomosis techniques*

The gold standard for anastomosis is suturing using needle and thread. Other techniques include chemical methods such as glue (Gluburan) and energy methods such as heat and laser to “weld” tissue together. Due to the simplicity, glue-based methods are attractive but the majority is used for surface wounds and they are not specified for internal use. These glues may also have toxic side effects [11]. Energy-based methods (lasers) are still experimental where early results have shown that the healing of tissue after it has been heated is not ideal [12-13]. Endoluminal magnets have also been explored independently by Obara and Daniel but they have not gained traction in the community. Suturing was selected as the one with minimal risk.

E. *Image guidance and automation*

The system will use a set of stereoscopic cameras that recreate the same optical features and properties as those found on an endoscope. The image guidance algorithm would automatically register, segment and track the vessel openings. The image guidance system must be able to recognize features as small as 1 mm. The Cartesian position of the opening is sent to the robotic controller for tracking the tip position.

III. SYSTEM DESIGN

KidsArm is composed of 4 subsystems: anastomosis tool, robotic arm, robotic controller, image processing unit and user interface. (see Figure 1).

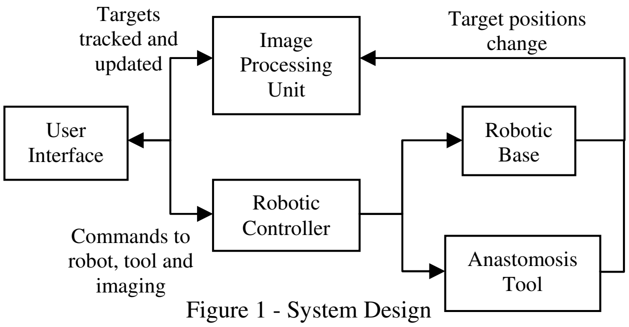

Figure 1 - System Design

A. *Anastomosis Tool*

The anastomosis tool makes use of the concept of a Covidien SILSstitch™[14], with 2 joints providing pitch and roll of the tip, plus an additional active grasper capable of moving forward and reverse for thread management. The SILSStitch™ is a laparoscopic suturing device that has two jaws where the clinician can pass the suture needle between the two jaws. The device allows the surgeon to perform single interrupted sutures using only one tool. The manual handle of the tool was replaced with a motor assembly to actuate the tool functions: opening/closing the grasper and passing the suture needle to/from each jaw. The total number of degrees of freedom is 6.

An analysis of suturing videos and tasks showed that it is important to control the thread to prevent tangling. To maintain this as a single port suturing tool, a thread management system was added to the SILSStitch. The thread management system is based on a flexible neurobiopsy device (see Figure 2). The biopsy tool has been modified so that it can extend, grab and retract the suture to provide sufficient tension and cleared away from the target suturing area.

In order to reduce the design challenges for this work, the Anastomosis Tool body was scaled up such that it could go through a standard 10mm trocar for proof-of-concept purposes. As a result of the scaled-up, the target mockup vessel was selected to be 10mm in diameter as well.

A 6 degree of freedom (DOF) load-cell (AT Mini-40 by ATI Automation) was mounted between the rear of the Anastomosis Tool and the mounting plate of the Robotic Arm. The load-cell measured forces and torques detected at the tip of the tool where this was used to provide feedback control to avoid excessive forces being exerted on the tissue.

All tool states, commands and load cells readings were connected to the robotic controller via a Quanser QuARC interface.

The additional joints and thread management system changes the tool from being a standard laparoscopic tool in to a robotic single port suturing system.

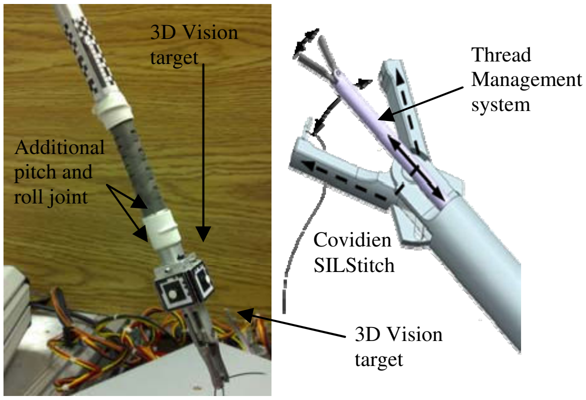

Figure 2 – Left: Anastomosis Tool (Thread management tool retracted and not visible) Right: CAD Model of anastomosis and thread management tool

B. *Robotic Arm*

A Denso VP6 series 6DOF articulated arm is used for carrying the Anastomosis Tool [15]. The 6 joints on the Robotic Arm combining with the pitch and roll joint on the Anastomosis Tool provide a total of 8 DOF. This allows KidsArm to pivot about the suturing tool within a trocar as typically performed during laparoscopic surgery. The Denso VP6 was selected for its low weight (~15 kg), small physical footprint (15cm x 15cm base) and high repeatability (+/- 0.02mm). Due to its' size, the payload capacity of the system is 2.5 kg which required the addition of a counterweight to accommodate the heavier anastomosis tool. (see **Figure 3**).

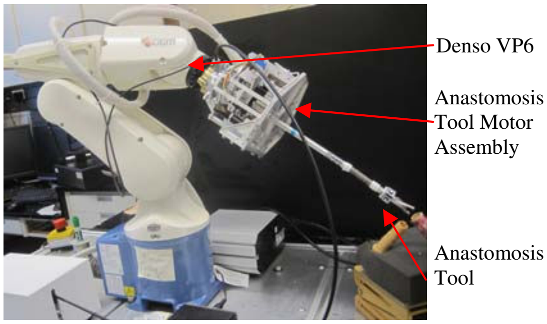

Figure 3 - Denso with Anastomosis Tool

C. *Robotic controller*

The robotic controller consists of a Windows based PC connected to two amplifier units, one for the Robotic Arm provided by Quanser specifically for the Denso VP6 and the other made up of Copley's Accelnet Micro Panels for the Anastomosis Tool. Both units are made up of servo amplifiers that receive analog commands from the PC and regulate the current on its corresponding motor at the joints on both the Robotic Arm and the Anastomosis Tool.

The control software is designed and implemented in Simulink, and executed using Quanser's QuaRC hardware-in-the-loop software. The inverse Jacobian algorithm resolves the Cartesian position of the selected suture points and the Tool tip from the Image-Processing Unit into the corresponding joint rate command to be executed at each of the Robotic Arm's and the Tool's joints. The core controller algorithm then takes the joint rate commands and converts them into motor analog signal through a specially-designed joint servo which calculates on-the-fly during operation the optimal control loop gains to achieve better trajectory-tracking accuracy in motion. There is also a separate tool joint servo algorithm for the operation of the SILStitch tip mechanism and the active thread-management grasper. Besides the default image-guided motion mode, master-slave via a hand-controller is also available via a teleoperation algorithm. A state-machine handles the various operating modes and states as per the signal issued from the user interface.

To ensure that the Robotic Arm will properly insert the Tool tip to the suture point, the control system has a feature that automatically generates a trajectory adapting to the environment. Given the position of the suture point as well as the opening of the tubular vessel by the Image Processing Unit, the control system adjusted the trajectory connecting the current Tool tip position to the destinations based upon how the vessel is positioned and oriented. Consequently, the Tool tip would always enter the vessel with its jaws clearing the opening edges of the vessel without collision before settling down at the destinations for needle-deployment.

D. *Image Processing Unit*

The Image Processing Unit (IPU) is responsible for providing the image-guidance input to the robot and tool controller. A block diagram of the IPU is shown in **Figure 4**.

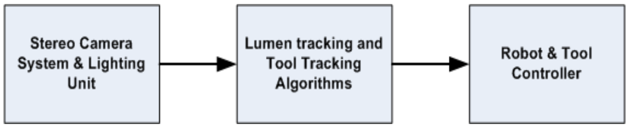

Figure 4: Image Processing Unit Block Diagram

A stereo camera and a lighting unit form the input sensor for the IPU. The stereo camera system consists of a pair of synchronized commercial industrial Basler cameras (Navitar aCA 1300 30gc) , which are selected to mimic those found in medical grade fixed endoscopes. A high intensity fiber light source was used as the lighting unit. The cameras are separated side by side by 4 cm and held in place by a flexible universal joint. The average distance from the camera to the surface of the target area is 12 cm.

3D reconstruction, image rectification and camera calibration functions from the OpenCV library was used to obtain the 3D point cloud data of the mockup tubular vessels. Image feature extraction, tool target tracking and deformable lumen tracking algorithms were implemented as part of this project. The PCL library was also used for 3D point processing.

The data flow diagram of the IPU are shown in **Figure 5**.

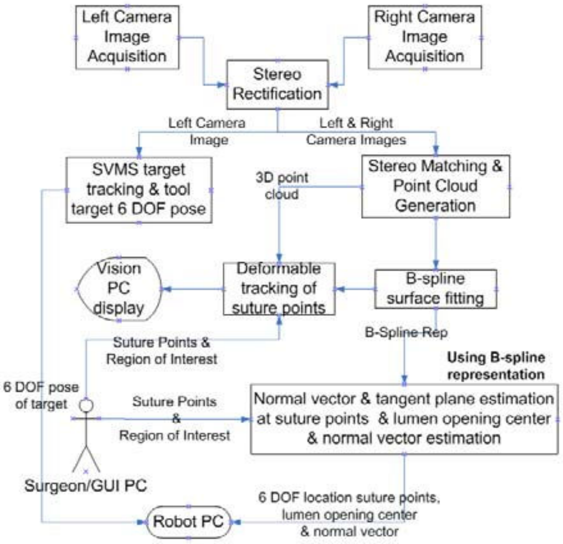

Figure 5: Data flow diagram of the Image Processing Unit.

Using the semi-global block matching function of the OpenCV library, the IPU generates the disparity of the object in view through the detection of the natural surface features that is applied onto the tubular vessels to represent the appearance of real lumen found inside human body, and as a result 3D point clouds are created that depicts the position of any given point within the field-of-view of the cameras.(see **Figure 6**)

A variety of image feature descriptors have been used to extraction and tracking [16]. For this work, a 2D/3D based approach was used for the Deformable vessel tracking method. 2D image features are first matched between the previous and current image frames obtained from the master camera. A 3D based approach was used for Deformable vessel tracking. The 2D image features are first matched between the left and right images to compute their 3D location. The matched 2D features was filtered by the epipolar constraint and only the 2D features whose disparity values were within the predefined range will pass to the next step. The rigid transformation is solved by 1) matching the 2D features (SIFT) between the previous and current image frames to establish the correspondences between the 2D-3D features; 2) Using Random Sample Consensus(RANSAC) to solve the 6DOFs rigid transformation by using the 3D locations of the 2D features computed in the previous step. The 3D point cloud obtained at each frame was first fused with the left camera image features and then fitted with a B-Spline surface. From this B-Spline surface representation, a coordinate frame is computed at each suture point.

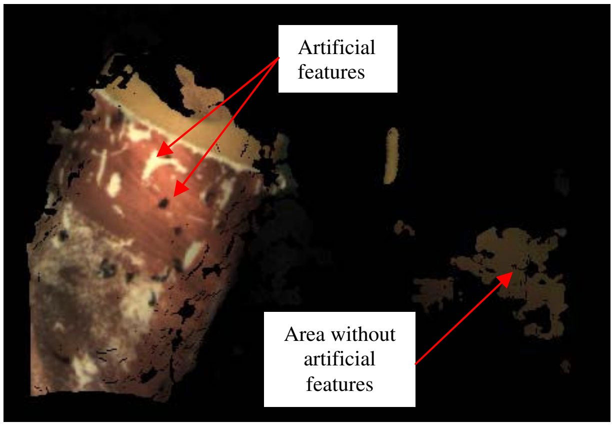

Figure 6 - 3D Point Cloud (Left: 3D reconstruction with artificial features, Right: 3D reconstruction with original)

When the user selects a suture point from the User Interface, the IPU converts that into a 3D point along the surface of the B-spline model. Using multiple user-selected suture points, the center of the vessel opening is calculated based on the instantaneous surface normal from the B-spline model. Both the suture point and the vessel opening positions are sent over to the Robot PC, such that the Robotic Controller can execute the corresponding anastomosis motion of the Tool by properly inserting the suture needle at the Tool tip into the vessel opening center.

When the target vessel is moved or deformed, the B-spline model accommodates accordingly and with the established geometric relationship of each suture point with respect to the structure of the vessel, the suture point as well as vessel opening positions are updated such that the system can react to the change in position or form of the target vessel and adjust the motion as required.

On the other hand, the IPU also detects the unique 3D features on the Tool target, which is designed by MDA and previously used on various space programs. The target mounting near the tip of the Anastomosis Tool gives the true position feedback of the Point-of-Resolution (POR) to the Robotic Controller, which is tracked by the IPU through the left camera image.

Together with the position of the suture point(s) and the Tool POR position, the IPU provides input to the control system for generating the motion command required to bring the tip of the Anastomosis Tool to the suture point via the vessel opening calculated. Registration of the Tool tip and the suture point positions onto the camera frame is done automatically with no user intervention required.

E. User Interface

The user interface consists of 2 parts: a 3D monitor and a touch screen for user input. The interface was designed to be a simple and intuitive input device for surgeons. The surgeon operator would select the points for the sutures by touching the screen and s/he would be able to view the actual worksite view in 3D. The touch screen also acts as a console to provide various parameters such as joint positions, errors, tool status and etc. The workflow is as follows: surgeons view the 3D image of the target area, s/he selects and confirms each of the individual suture points on the touch screen, s/he initiates the motion, KidsArm goes to the first point and applies the first suture and returns to home position and this is repeated for all the suture points.

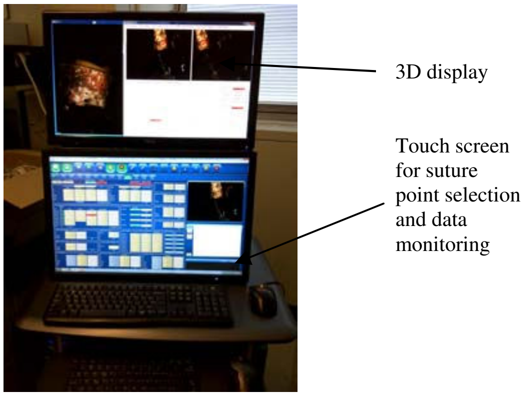

Figure 7 - User Interface

IV. RESULTS

The KidsArm is able to successfully operate in two modes: master-slave mode and auto mode. In the master-slave mode, the system can be driven in a POR state where the operator commands the position (XYZ) and orientation (pitch, yaw, roll) of the tip. An alternative state is the joint state where each of the Denso and anastomosis tool joints is controlled individually. In auto mode, the tip position of the anastomosis tool is moved to the first suture point through the feedback from the image processing unit and 3D point cloud. The actual opening and closing of the SILStitch requires the operator to execute each of the commands. During this function testing, it was noted there is some mechanical coupling associated with the added pitch and roll joints where under certain pitch configurations, there was drift and resistance to roll about the tool axis. Otherwise, KidsArm successfully performed all the function POR and joint motion tests. The thread-management mechanism on the other hand would be tested for functionalities and performance in a future phase.

In the performance testing, KidsArm was tested under 2 scenarios: side to side suturing represented by a silicone ridge on a test pad and end to end suturing represented by silicone tubes. For the side to side suturing, a silicone test pad produced by 3DMed used for laparoscopic teaching was the target. The test scenario involved selecting three points on the silicone ridge. As shown on **Figure 8**, KidsArm successfully sutured 3 points on the silicone test pad with a pattern projected on the surface. The suture points were within approximately 2 mm of the targets.

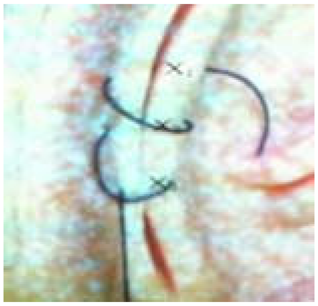

Figure 8 - 3 stitches (Side to Side)

For the end to end suturing, a pair of silicone tubes was mounted and a printed texture pattern was placed on the tubes. In this configuration (see Figure 9), image feature extraction, tracking and tool workspace issues made this task much more difficult. For this scenario, KidsArm was only able to complete 4 sutures on a single lumen before encountering either a visual issue (losing sight of the tool target) or workspace issue (joint limits). The challenge was the tubular elements would deform up to 1cm and can be compressed so the lumen opening is closed. As such, the previously identified targets would not be visible. Due to the restrictions, suturing on the opposing side was not possible. The resulting sutures were in correct location but precise measurement was not possible.

Figure 9 - End to end suturing

V. DISCUSSION

KidsArm showed that it is feasible for robots to perform some degree of autonomous suturing. For side-to-side suturing, Kidsarm was able to visualize, insert and suture 3 points. However, the end-to-end suturing was more challenging as there was a greater amount of surface deformation and restricted workspace.

In both scenarios, three common challenges were identified: feature identification, deformable surface tracking and workspace constraints. The lack of features on the silicone surface made image feature registration and tracking a significant challenge. To address this problem, artificial features were projected on to the surface using a projector or attached on to the surface. Attaching a new layer on the surface would not be practical in real tissue but it shows that having visible features is an important aspect of tissue tracking. This texture pattern was a series of randomized black and white spots. This texture pattern greatly improved the ability of the image processing system to generate a 3D point cloud. For the ridge target on the test pad, this was not a problem as target points could be ascertained. However, the tubular vessels were not straightforward and required a texture layer. More so, the system was quite sensitive to the depth of the objects and ambient light conditions. An external fiber optic projector was used to illuminate the area.

In addition to the lack of features, the dynamic nature of the tubular elements cause issues in our b-spline algorithms as nonlinear movements would cause the system to lose the point. There would be cases where the system was able to see the tool target but not the suture target. Ideally, larger field of view of cameras would have helped to better capture the scene and 3D map. Future work will require using a base with a large workspace and cameras with a wider field of view to avoid losing critical elements such as the suture target.

One of the key objectives of KidsArm is attempting to reduce what is traditionally a dual-hand operation of anastomosis into a single instrument with smart mechanisms. The SILS Stitch's needle-passing concept between two complimentary jaws was effective in its native hand-held instrument form, in that it streamlines the otherwise dual-hand operation of sewing. However the lack of a second instrument to manage the suture in the KidsArm concept means additional joints were required which added to the complexity of the Tool design. Also the straight needle design means the vessel opening needs to have a substantial size in order for the Tool tip to access. To ensure the needle does not collide against the vessel opening edge, the complexity of the Tool tip motion trajectory and range of motion required by the Tool (and hence the robot moving about the trocar) increased significantly. In addition, the SILSStitch relies on the surgeon's feel on the handle to ensure a successful needle-pass between the two jaws by the "feeling" at their fingers which is sufficient to accommodate for the joint flex inherit in the design concept; migrating the concept to a robotic application with the compliance in the transmission design, however, means that a complicated combination of position and force feedback for the jaw actuation and needle-passing is required in order to properly carry out the sewing action. A revamp of the tool design is required in the future phase of smart anastomosis development to improve on the efficiency and efficacy of the mechanical delivery of a suturing needle to the surgical site.

In order to mimic the current state-of-the-art of the pediatric surgeries, KidsArm was designed to accommodate laparoscopic motion by means of introducing additional joints at the distal end of the Anastomosis Tool. We encountered significant challenges in packaging up to six independent joints into a limited space. The resulting Anastomosis Tool experience issues in joint flex, backlashes unaccounted by position sensors (due to the amount of transmission chain outboard of the sensors), joint motion coupling etc. – all of which were somehow compensated by the IPU Tool tip tracking to a certain extent but the overall system processing rate suffered. During the master-slave mode we demonstrated the various anastomosis motion the Tool can carry out via a virtual trocar, however for image-guided mode the system needs faithful joint position feedback in order to direct the needle to its intended suture points accurately. In the next development effort of the Tool, more investigation effort is needed on miniature position sensor that can be implemented at or nearer to the tip as telemetry for the system in order to perform the visual servoing properly.

We also demonstrated the feasibility in using optical cameras to provide accurate position navigation and guidance for the anastomosis process. By using open-sourced computer-vision algorithms such as those from OpenCV, we managed to create a prototype setup that illustrate the identifying of positions of a given object, locating the reference features on the that object as well as tracking the motion and even deformation of such object. With a somewhat structured layout, we observed that it is possible to use these computed information to allow surgeons to preselect points of interest on a computer screen and the system would automatically adjust their positions according to the detectable change in shape and location of the vessel. These investigation findings provide an encouraging first step towards ultimately proving the KidsArm concept for realistic surgical situations.

VI. CONCLUSION

The first phase of the KidsArm project produced a proof of concept image-guided anastomosis robot aimed at neonatal and pediatric patients. The system showed that it is possible for robots to perform automatic suturing under endoscopic video guidance. However, more work is required in areas such as: reducing size and mass of the anastomosis tool, improving the robustness of image feature extraction/tracking algorithm and enlarging the workspace. If these issues can be addressed, image-guided robotic system can help eliminate or minimize the amount of time spent on suturing.

ACKNOWLEDGMENT

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