# Cooperative Control with Distal Manipulation for Fetoscopic Laser Photocoagulation

G Dwyer[1], C Bergeles[2], F Chadebecq[1], V Pawar[3], E. Vander Poorten[4], S Ourselin[2], J Deprest[5], P De Coppi[6], T Vercauteren[2], D Stoyanov[1]

*[1]Surgical Robot Vision Group, CMIC, University College London (UCL), [2]Translational Imaging Group, CMIC, UCL, [3]TouchLab, UCL, [4]Dept. Mechanical Engineering, KU Leuven, [5] University Hospital Leuven, [6]Institute of Child Health, UCL*

*george.dwyer.14@ucl.ac.uk*

## INTRODUCTION

Fetoscopic Laser Photocoagulation (FLP) is a minimally invasive fetal intervention used to treat Twin-Twin Transfusion Syndrome (TTTS)[1]. TTTS is a placental defect that causes an imbalance in the blood flow between fetuses, which can result in death or severe impairments. During the TTTS procedure, the surgeon manually manipulates a rigid (either straight or curved) fetoscope in order to observe the placenta and selectively coagulate vessels to sever the flow of shared blood supply. The process requires for the surgeon to manually scan the surface of the placenta to determine which vessels need to be coagulated in order to ablate vascular joins. This is technically difficult because the fetoscope must be kept approximately 10 mm from the placenta to deliver appropriate laser power for coagulating vessels while refraining from physical contact with the placenta which can lead to complications. The procedure can possibly be improved by increasing the dexterity and stability of the fetoscope by actuating the tip of the instrument and enhancing the stability of the instrument by an active robotic arm which assists the manipulation of the fetoscope. This could also assist in techniques to map the placenta as the position and orientation of the endoscope is known[2], [3].

Continuum mechanisms have been used in surgical robotics in order to potentially facilitate smaller diameter instruments and larger number of degrees of freedom (DOF). However, these mechanisms are often applied to single port surgery, intravascular or neurosurgery, where the mechanism is fixed outside the body (proximal to the surgeon) and controls all the movement from within (distal to the surgeon). In comparison, more established articulated mechanisms such as the Da Vinci surgical robot utilise both proximal and distal motion from the parallel linkage and wrist joints separately. This approach results in seven active DOF, four proximal and three distal (one of which being the end effector). While continuum robots, such as concentric tube robots [4], [5], have demonstrated over six DOF, they often have a comparatively small workspace and low pose accuracy. Even though small profile mechanisms have been presented using concentric tube robots coupled with a passive proximal arm for single port prostate surgery[6], the comanipulation of the device was not fully explored. The concentric tube robot was inserted through an endoscope with a working channel allowing the endoscope to be manipulated with the passive arm and the robot to be manipulated relative to the endoscope.

This paper presents the mechanism design and control of a two DOF concentric tube robot combined with the coupling to a seven degree of freedom robotic arm constrained to a remote centre of motion. The combination of the two actuation mechanisms allows the end-effector to be positioned with five degrees of freedom. The mechanism was designed to be compact and attachable to the proximal robotic arm. A cooperative control scheme is designed and implemented allowing the position of the camera to be controlled by the operator while the orientation of the tip is automatically controlled to remain perpendicular to the desired imaging plane.

## METHODS

**Instrument Design**: The distal actuation mechanism was designed to be compact and easily attached to the proximal actuation mechanism. The mechanism provides two DOF to manipulate the axial rotation and translation of the nitinol tube. Both DOF are actuated from the back of the mechanism through a lead screw for the tube translation and a square shaft for the tube rotation following a similar design presented by Burgner *et. al.* [7]. A carriage is used to transmit torque from the motors to the nitinol tube as shown in 1a. The carriage contains the lead screw nut and a gear with a square 10 mm bore constrained in place with two rotational bearings either side. A linear bearing to provide the interface between the gear and square shaft is printed using wear resistant filament (iglide Tribo-Filament, Igus). The use of the carriage allows the inner tube to be easily swapped without dismantling the mechanism. The inner tube is fixed to a spur gear and two rotational bearings positioned either side of the gear. This is held in the carriage by fixing both bearings in place. The mechanism housing and carriage were 3d printed using PLA on a Ultimaker 2 and the inner tube couple using tough resin on a Formlabs 1+.

The instrument was then assembled with a steel outer tube with an inner and outer diameter of 1.8mm and 2.4mm respectively, and a nitinol inner tube, 1.4mm and 1.59. Dynamixel MX-28 motors (Robotis Inc., USA) are attached to the lead screw and square shaft at the back of the mechanism shown in 1b.

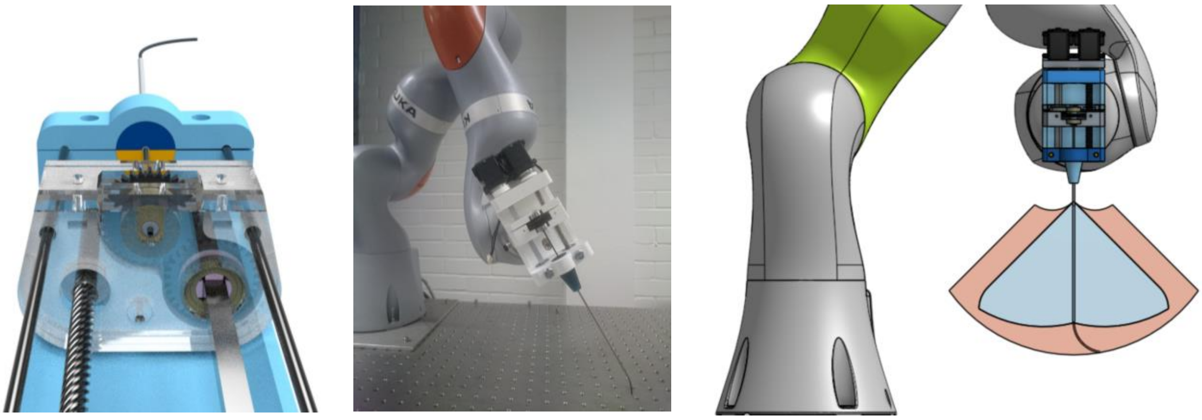

*Figure 1: a) CAD render of the distal mechanism and workings of the carriage. b) The assembled mechanism coupled to a KUKA iiwa robot arm operating as the proximal co-manipulator. c) The reachable (red) and orientated (blue) workspace of the instrument*

**Instrument Control**: The principle of this mechanism relies on the bending stiffness of the outer straight tube to be significantly larger than the stiffness of the inner tube, causing the shape of the inner tube to conform to the shape of the outer. This allows the overall shape of the instrument to be assumed as the shape of the outer tube and then from the tip of the outer tube an arc with the curvature of the inner tube, $k$, length extruded from the outer tube, $l$ and bending plane given by the orientation of the tube, $\varphi$. With the length and orientation given by the motor encoder values. This can be represented as:

$$^{Shaft}T_{Tip} = T_{RotZ}(\varphi)\, T_{trans}\left(\frac{1-\cos(kl)}{k}, 0, \frac{\sin(kl)}{k}\right) T_{RotY}(kl) \quad (1)$$

Where $T_{RotZ}(\varphi)$ is a transform containing a rotation around the Z axis of angle $\varphi$ and $T_{trans}(x, y, z)$ is a transform containing a translation along the X, Y and Z axis respectively.

**Proximal Co-Manipulation**: An articulated arm (KUKA LBR iiwa 7 R800) is used for the proximal manipulation of the instrument. The arm is a seven DOF arm with torque sensors on each joint. Minimally invasive surgery requires the instruments used to be constrained to a remote centre of motion (RCM) due to the small incisions used to access the inner anatomy through a port. A RCM constrains the motion to four DOF, translation, $r$, and rotations along the instrument shaft (Z axis), and extrinsic rotations of the X and Y axes. However, as the distal actuation mechanism provides continuous rotation along the z axis, the z axis rotation is restricted. From the RCM, the transform of the tip of the instrument shaft, in this case the outer tube, can be shown as:

$$^{RCM}T_{Shaft} = T_{RotZ}(\alpha) T_{RotY}(\beta) T_{RotZ}(-\alpha) T_{trans}(0, 0, r) \quad (2)$$

The KUKA direct servo application programming interface (API) provides the external force applied to the flange of the arm, after calibrating the weight of the tool attached. With the coordinate frame in the same orientation as $T_{RCM}$ the x, y and z axis forces are mapped to incrementing the desired x, y and z position.

The desired position can then be mapped to $\alpha, \beta$ and $r$ through:

$$\alpha = \tan^{-1}\left(\frac{y}{x}\right),\ r = \sqrt{x^2 + y^2 + z^2},\ \beta = \cos^{-1}\left(\frac{z}{r}\right) \quad (3)$$

A manually tuned PID controller is then implemented to minimise the external force on each axis by manipulating position of the arm. In order to keep a consistent orientation, the distal actuation mechanism is constrained to a certain position according to the current position of the instrument shaft. Firstly, the orientation of the tube, $\varphi$, that aligns the bending plane of the tube perpendicular to the desired imaging plane; and secondly, length of the tube extended, $l$, must be found to achieve the perpendicular constraint. The orientation of the tube can be found by finding the difference between $T_{RCM}$ and $T_{Shaft}$ around the z axis. While the length the can be found by finding the angle between the RCM z axis and the instrument shaft axis, $\theta$.

$$\varphi = \alpha,\ \theta = \beta,\ l = \frac{\theta}{k} \quad (4)$$

As these constraints are resolved using the current position they are evaluated at the same frequency as the cooperative controller (avg 200Hz) to ensure any error in the tip orientation remains as low as possible.

## RESULTS

The workspace of the presented instrument was calculated through simulation. The limits applied to each of the kinematic variables were:

$$\alpha \in [0, 2\pi], \beta \in \left[0, \frac{\pi}{4}\right], r \in [0, 140],$$
$$\varphi \in [0, 2\pi], l \in [0, 50]$$

Two workspaces were calculated, the reachable workspace and the orientated workspace, which is the workspace in which the device can adhere to the perpendicular constraint, eq. 4. This resulted in workspaces of 5607678.9 $mm^3$ and 2377427.2 $mm^3$ for the reachable and orientated workspace respectively. The orientated workspace allows a planar surface to be scanned with the area of a circle with a diameter of 218.5 mm.

## DISCUSSION

We have developed a new concentric tube robot design for fetoscopic procedures. The mechanism has a small diameter of 2.4mm in order to minimise entry access trauma. Our device, while still preliminary, has the advantage of being mounted onto a compliant robotic arm that can sense interaction forces. The control system for this robot is developed to allow improved fetoscopic surgery that can observe and ablate placental vasculature to ensure complete and accurate photocoagulation that severs the TTTS condition. In our future work we would like to extend this platform to include visual servo methods using both ultrasound and fetoscopic information as well as more advanced co-manipulation control.

## ACKNOWLEDGEMENT

This work was supported through an Innovative Engineering for Health award by Wellcome Trust [WT101957]; Engineering and Physical Sciences Research Council (EPSRC) [NS/A000027/1] and the EPSRC- funded UCL Centre for Doctoral Training in Medical Imaging (EP/L016478/1).

## REFERENCES

[1] F. Slaghekke, E. Lopriore, L. Lewi, J. M. Middeldorp, E. W. Van Zwet, A. Weingertner, F. J. Klumper, P. Dekoninck, R. Devlieger, M. D. Kilby, M. A. Rustico, J. Deprest, R. Favre, and D. Oepkes, "Fetoscopic laser coagulation of the vascular equator versus selective coagulation for twin-to-twin transfusion syndrome : an open-label randomised controlled trial," *Lancet*, vol. 383, no. 9935, pp. 2144–2151, 2014.

[2] P. Daga, F. Chadebecq, D. Shakir, L. C. Garcia-Peraza Herrera, M. Tella, G. Dwyer, A. L. David, J. Deprest, D. Stoyanov, T. Vercauteren, and S. Ourselin, "Real-time mosaicing of fetoscopic videos using SIFT," *SPIE Med. Imaging Proc.*, vol. 9786, pp. 1–7, 2015.

[3] M. Tella, P. Daga, F. Chadebecq, S. Thompson, D. I. Shakir, G. Dwyer, W. Ruwan, J. Deprest, D. Stoyanov, T. Vercauteren, and S. Ourselin, "A combined EM and visual tracking probabilistic model for robust mosaicking of fetoscopic videos," *IEEE Proc. 7th Int. Work. Biomed. Image Regist.*, 2016.

[4] R. J. Webster, J. M. Romano, and N. J. Cowan, "Mechanics of Precurved-Tube Continuum Robots," *IEEE Trans. Robot.*, vol. 25, no. 1, pp. 67–78, Feb. 2009.

[5] P. E. Dupont, J. Lock, B. Itkowitz, and E. Butler, "Design and Control of Concentric-Tube Robots," *IEEE Trans. Robot.*, vol. 26, no. 2, pp. 209–225, Apr. 2010.

[6] R. J. Hendrick, S. D. Herrell, and R. J. Webster, "A multi-arm hand-held robotic system for transurethral laser Prostate surgery," in *IEEE International Conference on Robotics and Automation (ICRA)*, 2014, pp. 2850–2855.

[7] J. Burgner, P. J. Swaney, R. a. Lathrop, K. D. Weaver, and R. J. Webster, "Debulking From Within: A Robotic Steerable Cannula for Intracerebral Hemorrhage Evacuation," *IEEE Trans. Biomed. Eng.*, vol. 60, no. 9, pp. 2567–2575, Sep. 2013.