Project 15

DaVinci-Assisted Continuum Robot Navigation and Manipulation

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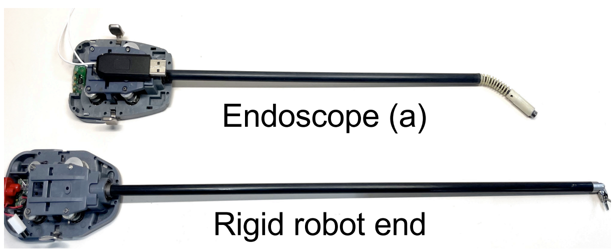
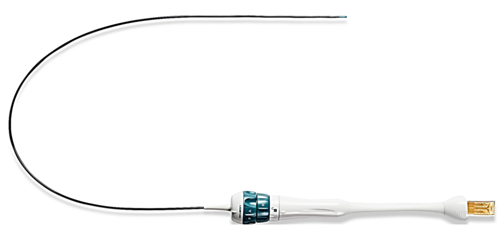
Project Summary

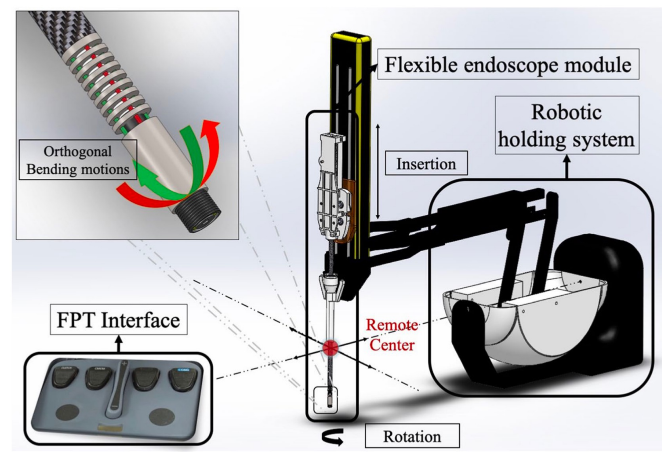
Goal: build a continuum robot navigation and manipulation system with tendon-driven continuum robot end to improve the reachability of the DaVinci robot arm.

- Redesign DaVinci Research Kit (dVRK) with flexible robot end (endoscope and Acunav catheter)
- Construct forward kinematics model of dVRK continuum robot end
- Apply ROS navigation and manipulation on redesigned dVRK





Acunav catheter: jnjmedtech.com/en-US/product/acunav-ultrasound-catheter

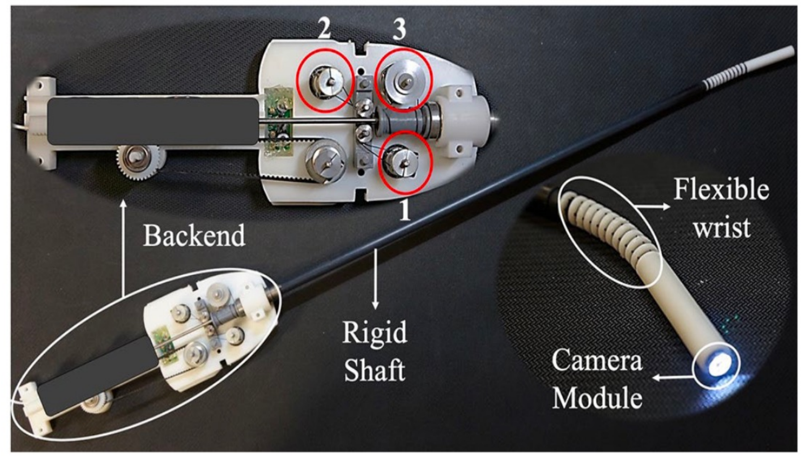


Patient Side Manipulator (PSM) kinematics with flexible endoscope[1]

Paper 1 detail

- **Title**: A robotic flexible endoscope with shared autonomy: a study of mockup cholecystectomy
- **Authors**: Chengzhi Song, Xin Ma, Xianfeng Xia, Philip Wai Yan Chiu, Charing Ching Ning Chong, Zheng Li
- **Journal**: Surgical Endoscopy(2020)

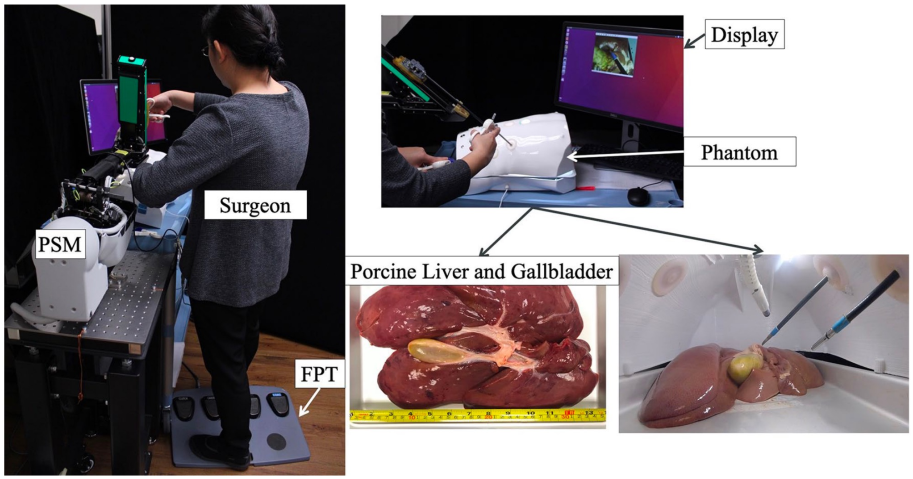
- **Relevance**:
  - Description of a dVRK-based robotic flexible endoscope(RFE)
  - Detailed description of clinical surgery task
  - Key to verifying robotic flexible endoscope's surgical performance



Flexible endoscope module with three motions: one rolling motion and two orthogonal bending motions [1]

Technical Approach

- **Mockup cholecystectomy of 3 endoscope systems**
  - Constrain robotic flexible endoscope to simulate rigid and manual endoscopes
- **User experience study with endoscopes**
  - Propose a NASA-TLX performance study to evaluate 3 endoscope systems



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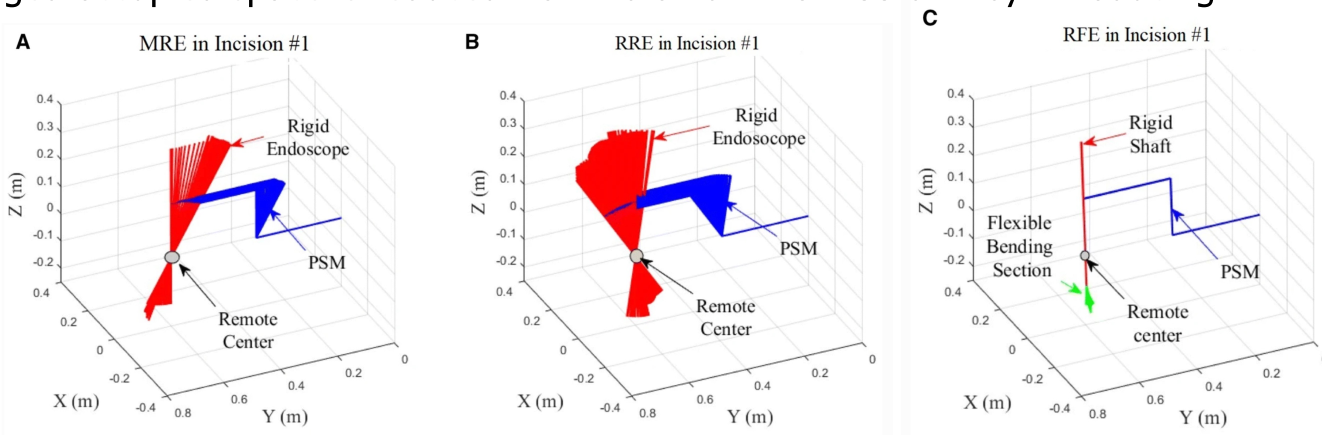
Experiment

- **Goal**: Endoscope occupied space measurement and comparison
- **Method**: kinematic modeling of the robotic holding system
- **Analysis**: draw motion sequences via dVRK joint values during phantom operation

- **Results summary**:
  - Occupied space of robotic flexible endoscope(RFE), robotic rigid endoscope(RRE) and manually controlled rigid endoscope(MRE) are recorded.
  - Averaged occupied space is reduced from 16.02 dm^3 to 2.33 dm^3 by introducing RFE.



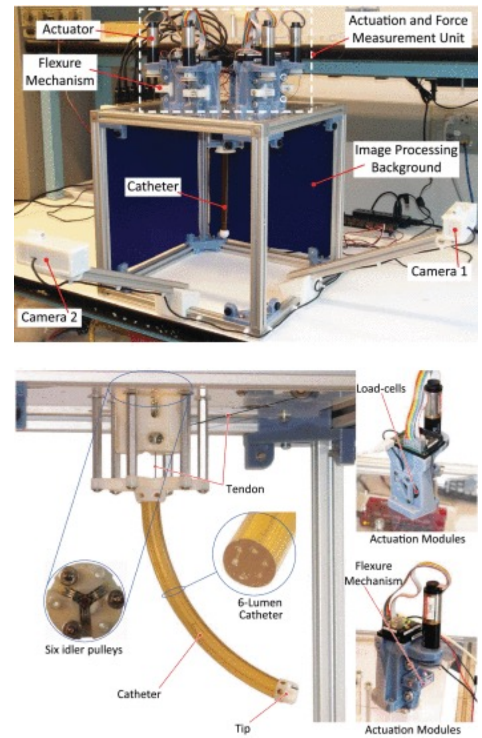
Critical Review

- **Pros**:
  - Paper does a good job at evaluating the behavior of robotic flexible endoscope
  - Successfully demonstrated the feasibility of applying dVRK with tendon-driven continuum robot in surgical application domain.
- **Cons**:
  - Paper lacks technical details in kinematic models and RFE actuation.
- **Key takeaway**:
  - Our work complements this paper by building dVRK-based tendon-driven Acunav catheter that will provide more actual and applicable work in surgical field.
  - Evaluate the performance of the RFE as surgical training tool.

Paper 2 detail

- **Title**: General Forward Kinematics for Tendon-Driven Continuum Robots
- **Authors**: Mohsen Moradi Dalvand; Saeid Nahavandi; Robert D. Howe
- **Journal**: IEEE Access

- **Relevance**:
  - Forward kinematics of tendon-driven continuum robots
  - Open-loop tip navigation and convergence
  - The impact of the number of tendons on accuracy



The developed modular continuum robotic system capable of manipulating robots with up to 6 tendons [2]

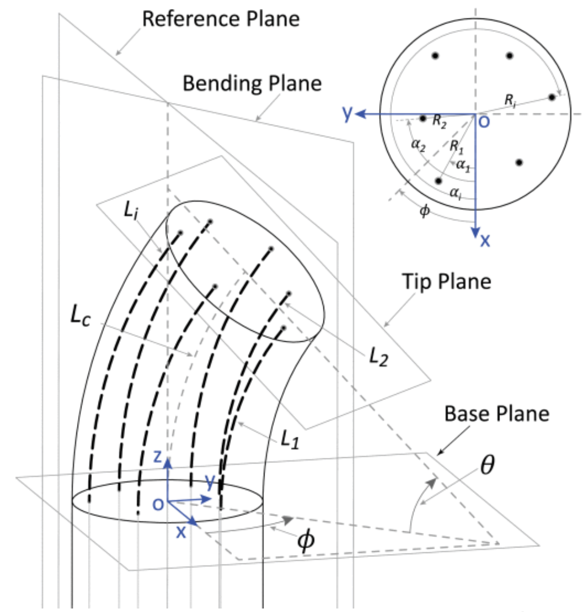
Technical Approach

- **Forward kinematics of n -tendon continuum robots**
  - The forward kinematics problem of continuum robots is to determine the beam configuration ($[\theta, \phi, L_C]$) for a given set of arbitrary actuator displacements (ΔL_{ai}).

$$\Delta L_{a_i} = \Delta L_i + \delta_i \quad i = 1, \ldots, n$$

$$\Delta L_i = (L_0 - L_c) + R_i \theta \cos(\alpha_i - \phi) \quad i = 1, \ldots, n.$$

$$\Delta L_{a_i} = g_i(\theta, \phi, L_c, n, R, A, E, I, L_0, R_t, A_t, E_t, L_{0_t}, R_1, \ldots, R_n, \alpha_1, \ldots, \alpha_n) \quad i = 1, \ldots, n.$$

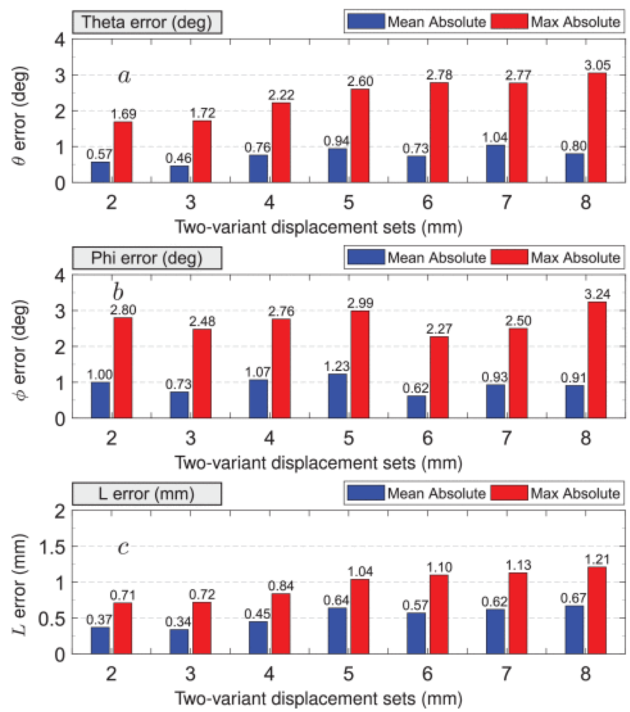


Schematic description [2]

Experiment

- **Goal**: evaluate the proposed forward kinematics algorithm
- **Method**: command a series of arbitrary actuator displacements
- **Analysis**: Compare beam configurations to algorithm for actuator displacements.

- **Results summary**:
  - Occupied Mean absolute and maximum absolute errors
  - The error of ±0.5 deg and ±0.6 mm for the angular and linear parameters, respectively



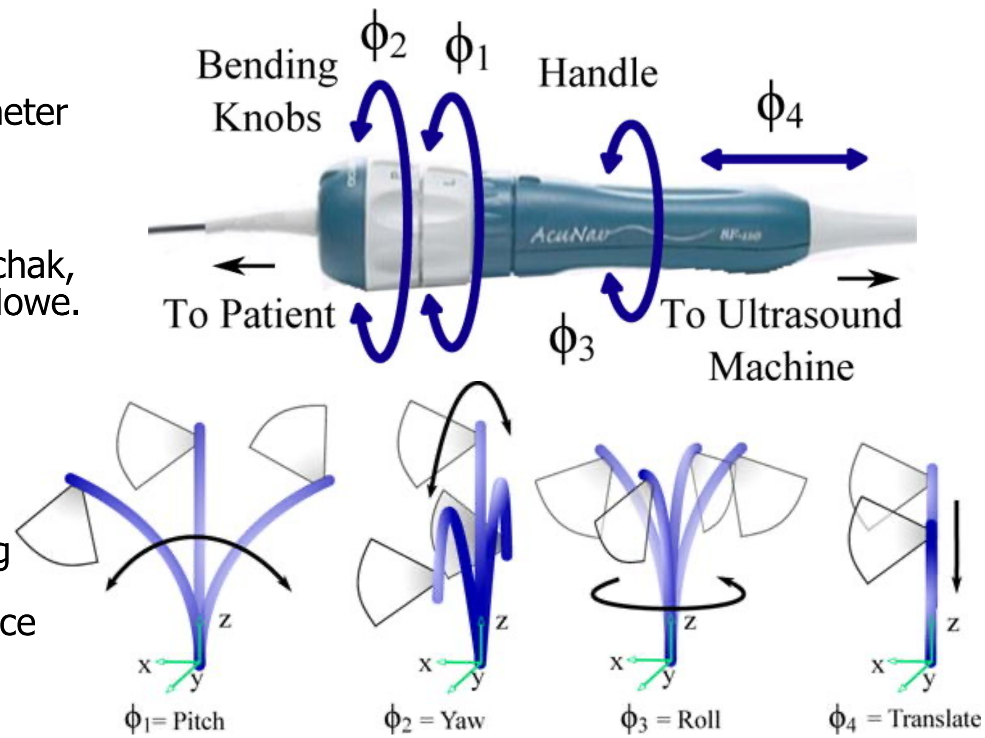
[2]

Critical Review

- **Pros**:
  - Paper does a good job at constructing the forward kinematics matrix
  - Successfully demonstrated the high precision of continuum robots..
- **Cons**:
  - Paper lacks error verification for large angle bending.
- **Key takeaway**:
  - General forward kinematics matrix
  - The evaluation of the impact of the number of driven tendons on accuracy.

Paper 3 detail

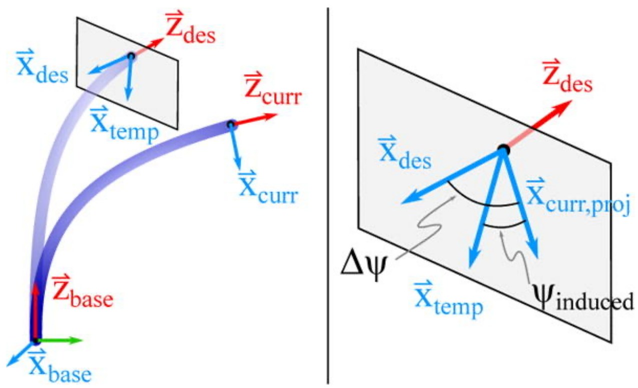
- **Title**: Compensation for Unconstrained Catheter Shaft Motion in Cardiac Catheters
- **Authors**: Degirmenci, Alperen, Paul M. Loschak, Cory M. Tschabrunn, Elad Anter, Robert D. Howe.
- **Journal**: IEEE International Conference on Robotics and Automation (ICRA) 2016.
- **Relevance**:
  - Forward, inverse kinematic, joint mapping model of AcuNav catheter
  - Closed loop tip navigation and convergence from disturbance
  - Advantages of surgical robot operation

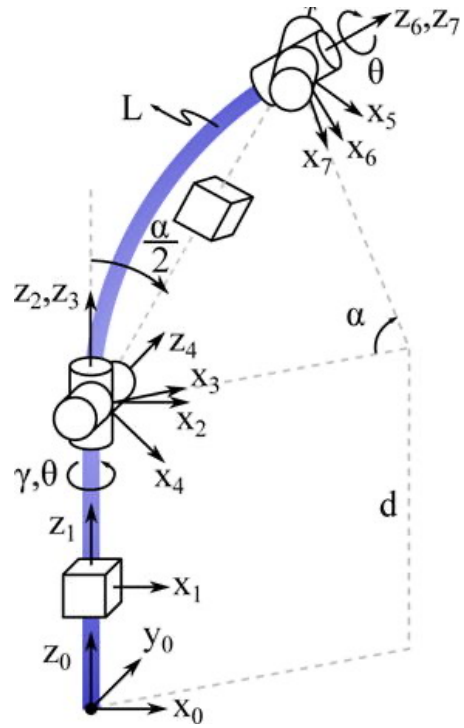


Degirmenci, A., Loschak, P. M., Tschabrunn, C. M., Anter, E., & Howe, R. D. *Compensation for unconstrained catheter shaft motion in cardiac catheters.* IEEE (ICRA) 2016. [3]

Technical Approach

- **Forward kinematics modeling of AcuNav catheter**
  - 4 DoF control:
    (AcuNav)Bending: 2 DoF
    (Robot) Rolling: 1 DoF
    (Robot) Translation :1 DoF
- **Forward kinematics**
- **The imager heading method**





D-H PARAMETERS

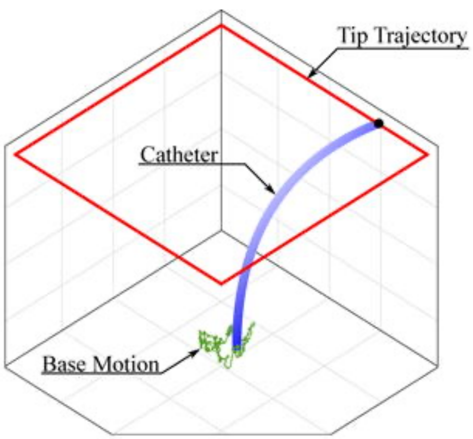
Link	a_i	α_i	d_i	θ_i
$0 \to 1$	0	0	d	0
$1 \to 2$	0	0	0	γ
$2 \to 3$	0	0	0	θ
$3 \to 3'$	0	$-\pi/2$	0	0
$3' \to 4$	0	$\pi/2$	0	$\alpha/2$
$4 \to 5$	0	$-\pi/2$	$2\frac{L}{\alpha}\sin\frac{\alpha}{2}$	0
$5 \to 6$	0	$\pi/2$	0	$\alpha/2$
$6 \to 7$	0	0	0	$-\theta$

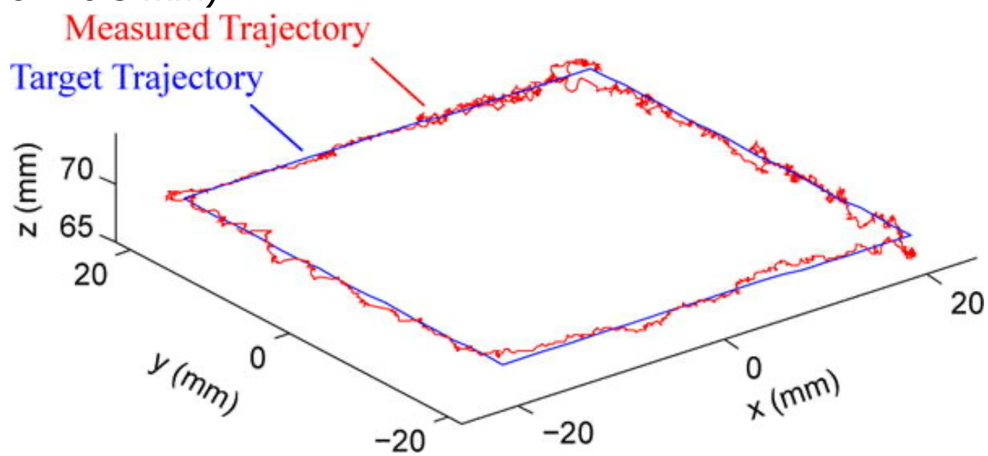
Degirmenci et al.,2016 [3]

Experiment

- **Goal**: Bench top motion
- **Method**: test tip moving on target trajectory
- **Analysis**: record the real motion of the tip and measure the error.

- **Results summary**:
  - the position of the catheter tip was maintained within the 1 mm position error threshold (measured error mean 0.83 mm, $\sigma = 0.3$ mm)





Degirmenci et al.,2016[3]

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Critical Review

- **Pros**:
  - Paper did a good job at navigating the motion of AcuNav catheter tip.
  - The forward kinematic and joint mapping function can be applied directly to our AcuNav catheter.
- **Cons**:
  - Paper lacks detailed kinematic values of AcuNav catheter.
- **Key takeaway**:
  - Detailed forward kinematic and joint mapping function of AcuNav catheter.
  - Successed on vivo animal testing, showing the advantage of surgical robot operation.

Conclusion

- RFE is feasible in dVRK system with verified surgical application(paper 1).
- The forward kinematics of general tendon-driven continuum robots are highly correlated to our current work(paper 2).
- The forward kinematics and joint mapping function of AcuNav catheter are highly correlated to our current work(paper 3).

Reference

[1] C. Song, X. Ma, X. Xia, P. W. Y. Chiu, C. C. N. Chong, and Z. Li, "A robotic flexible endoscope with shared autonomy: a study of mockup cholecystectomy," *Surg Endosc*, vol. 34, no. 6, pp. 2730–2741, Jun. 2020, doi: 10.1007/s00464-019-07241-8.

[2] M. Moradi Dalvand, S. Nahavandi and R. D. Howe, "General Forward Kinematics for Tendon-Driven Continuum Robots," in IEEE Access, vol. 10, pp. 60330-60340, 2022, doi: 10.1109/ACCESS.2022.3180047.

[3] Degirmenci, A., Loschak, P. M., Tschabrunn, C. M., Anter, E., & Howe, R. D. (2016, May). Compensation for unconstrained catheter shaft motion in cardiac catheters. In 2016 IEEE International Conference on Robotics and Automation (ICRA) (pp. 4436-4442). IEEE.

[4] JHU-dVRK. DaVinci Research Kit. GitHub, https://github.com/jhu-dvrk/sawIntuitiveResearchKit/wiki.


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