UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

itee PhD information technology electrical engineering

DIETI UNINA

Cristina Iacono

Automation of robot-assisted surgical procedures

Tutor: Fanny Ficuciello

Cycle: XXXV

Year: 3rd

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icaros

My background

- **MSc degree** — Automation Engineering at *"Università degli Studi di Napoli Federico II"*
- **Research group/laboratory** — prisma LAB, icaros
- **PhD start date** — 1st November 2019
- **Scholarship type** — Unina

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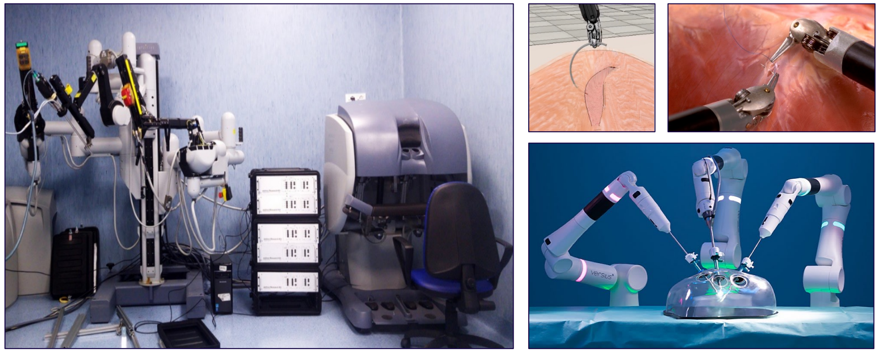
Research field of interest

Automation of robot-assisted surgical procedures



Summary of study activities

PhD courses:

- Matlab fundamentals
- Innovation management, entrepreneurship and intellectual property
- Statistical data analysis for science and engineering research
- Mathematics and Statistics for Life Sciences
- Strategic Orientation for STEM Research and Writing

MSc courses:

- Robot Interaction Control
- Visione per Sistemi Robotici
- Robotics Lab

PhD Schools: SIDRA 2021:

- Game Theory and Network Systems
- Soft Robots

Summary of study activities

Attended:

International Conference on Robotics and Automation (ICRA) 2020
Conference on New Technologies for Computer/Robot Assisted Surgery (CRAS) 2020
Italian Institute of Robotics and Intelligent Machines (I-RIM) 3D 2020
Italian Institute of Robotics and Intelligent Machines (I-RIM) 3D 2021
International Conference on Robotics and Automation (ICRA) 2022

Organized:

Conference on New Technologies for Computer Robot Assisted Surgery (CRAS) 2022

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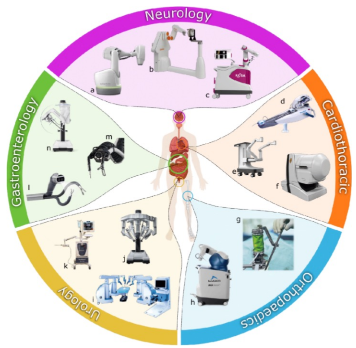
Surgical Robotics



Limitations:

- Still strongly depends on surgeon's abilities
- Limited vision on the surgical site
- Kinematically complex and repetitive tasks
- Lack of haptic feedback

Objective:

- Automation of surgical tasks in order to reduce surgeon errors, duration of procedures, trauma, and expense

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Autonomy in Surgical Robotics

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Yang, G.Z., Cambias, J., Cleary, K., Daimler, E., Drake, J., Dupont, P.E., Hata, N., Kazanzides, P., Martel, S., Patel, R.V. and Santos, V.J., 2017. Medical robotics—Regulatory, ethical, and legal considerations for increasing levels of autonomy. *Science Robotics*, 2(4), p.eaam8638.

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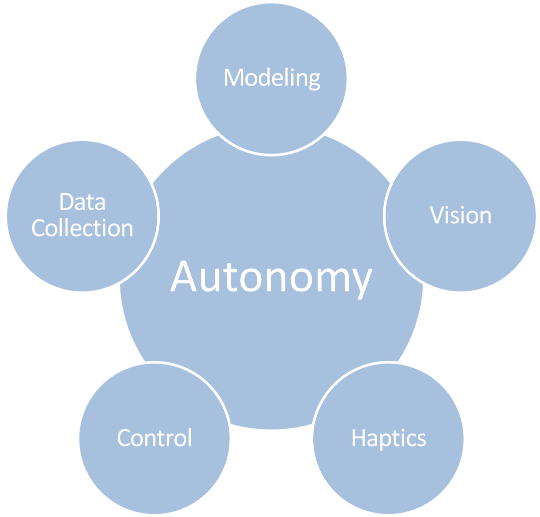
Contribution



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DVRK Dynamic Model Identification for sensor-less force estimation

Problem:

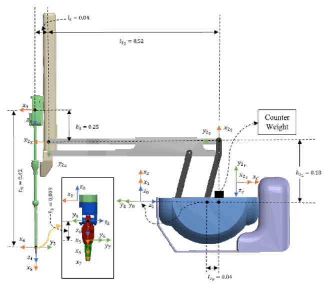
- Control strategies must take into account the robot's interactions with the dynamic and unstructured surgical environment

Solution:

- Identification of the PSM dynamic model

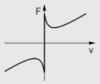
Previous Solutions:

- Fontanelli, Giuseppe Andrea, et al. "Modelling and identification of the da Vinci research kit robotic arms." 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2017.
- Wang, Yan, et al. "A convex optimization-based dynamic model identification package for the da Vinci Research Kit." IEEE Robotics and Automation Letters 4.4 (2019): 3657-3664.



DVRK Dynamic Model Identification for sensor-less force estimation

Method

- Friction estimation
  - Stribeck effect 
  - Superposition method
- Augmented Lagrangian Particle Swarm Algorithm (ALPSO)

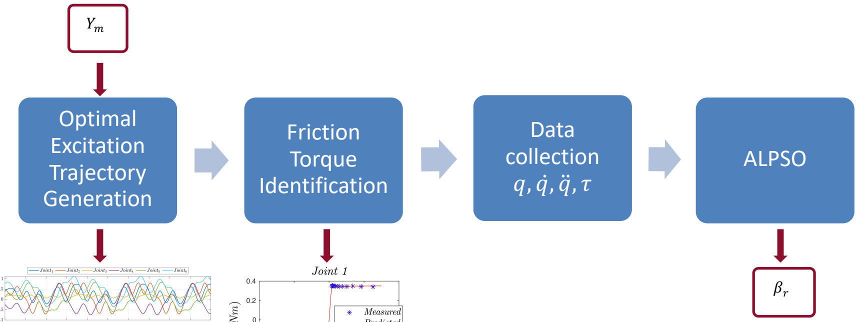
$$\boldsymbol{\tau}_f = \frac{2}{\pi}\arctan(c\dot{\boldsymbol{q}})\Big(\big(\boldsymbol{F}_c + (\boldsymbol{F}_s - \boldsymbol{F}_c)e^{-|\dot{q}|/\dot{q}_s}\big) + \boldsymbol{F}_v\dot{\boldsymbol{q}}\Big)$$

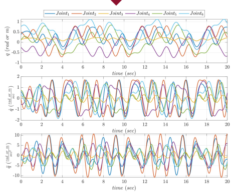
$$\begin{aligned}\boldsymbol{\tau}_i(\boldsymbol{q}_f^+) &= \boldsymbol{G}(\boldsymbol{q}_f^+) + \boldsymbol{\tau}_f(\dot{\boldsymbol{q}}_f^+)\\ \boldsymbol{\tau}_i(\boldsymbol{q}_f^-) &= \boldsymbol{G}(\boldsymbol{q}_f^-) + \boldsymbol{\tau}_f(\dot{\boldsymbol{q}}_f^-)\end{aligned} \;\; - \;\; \Rightarrow \;\; \boldsymbol{\tau}_f(\dot{\boldsymbol{q}}_f) = \frac{\boldsymbol{\tau}_i(\boldsymbol{q}_f^+) - \boldsymbol{\tau}_i(\boldsymbol{q}_f^-)}{2}$$

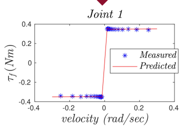
Constrained Optimization Problem

$$\begin{aligned}&\underset{\boldsymbol{\beta}_r}{\text{argmin}} \quad ||\boldsymbol{\tau}_m - \boldsymbol{Y}_m\boldsymbol{\beta}_r||^2 \quad \boldsymbol{\beta}_r \in \mathcal{D} \subseteq \mathbb{R}^r\\ &\text{subject to} \quad \begin{cases}\boldsymbol{g}(\boldsymbol{\beta}_r) = 0, & \boldsymbol{g}: \mathbb{R}^r \to \mathbb{R}^{m_e},\\ \boldsymbol{h}(\boldsymbol{\beta}_r) \leq 0, & \boldsymbol{h}: \mathbb{R}^r \to \mathbb{R}^{m_i}\end{cases}\end{aligned}$$

DVRK Dynamic Model Identification for sensor-less force estimation







joint	1	2	3	4	5	6	7
W	0.124	0.246	0.329	0.421	0.658	0.426	0.852
F	0.142	0.259	0.327	0.481	0.716	0.382	0.828
N	0.089	0.241	0.295	0.299	0.542	0.316	0.434

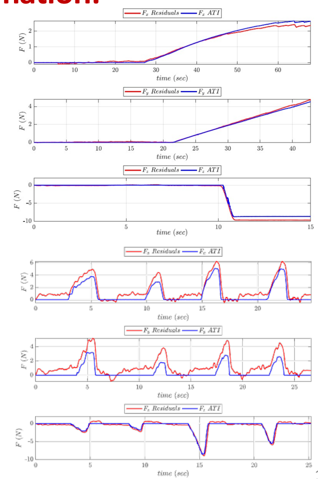
DVRK Dynamic Model Identification for sensor-less force estimation

Residual-based sensorless force estimation:

$$r = K_I\left(p - \int_0^t \left(\tau + C^T(q,\dot{q})\dot{q} - g(q) + r\right) ds\right)$$

$$\dot{r} = K_I(\tau_{ext} - r)$$

- For sufficiently large gains $r \simeq \tau_{ext}$
- Extimated Esternal Force $\hat{F}_c = \left(J_c^T(q)\right)^* r$



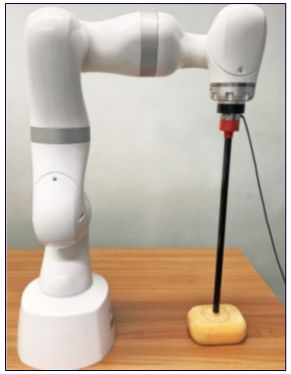
Products

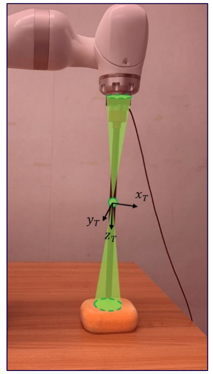
J1	O. F. Argin, R. Moccia, **C. Iacono**, F. Ficuciello, "da Vinci Research Kit Patient Side Manipulator Dynamic Model using Augmented Lagrangian Particle Swarm Optimization", **submitted** to IEEE Transaction on Medical Robotics and Bionics

Control framework for human robot interaction in medical robotics applications

Problem:

- Several medical robotics applications require an RCM constraint
- Reduced workspace to avoid touching dangerous areas



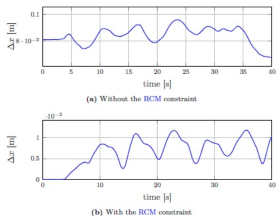


Control framework for human-robot interaction in medical applications

RCM constraint

$$\boldsymbol{p}_{RCM} = \boldsymbol{p}_i + \lambda(\boldsymbol{p}_{i+1} - \boldsymbol{p}_i) \quad 0 \leq \lambda \leq 1$$

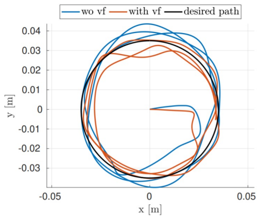
$$\dot{\boldsymbol{p}}_{RCM} = \boldsymbol{J}_{RCM}(\boldsymbol{q}, \lambda) \begin{bmatrix} \dot{\boldsymbol{q}} \\ \dot{\lambda} \end{bmatrix}$$



Manual guidance and Virtual Fixtures:

$$\boldsymbol{M}\ddot{\boldsymbol{p}} + \boldsymbol{D}\dot{\boldsymbol{p}} + \boldsymbol{K}\boldsymbol{p} = \boldsymbol{f} - \boldsymbol{f}_{VF}$$

$$\boldsymbol{f}_{VF} = \boldsymbol{K}_{VF}\boldsymbol{d} + \boldsymbol{D}_{VF}\dot{\boldsymbol{d}}$$



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Products

J1	C. Pecorella, **C. Iacono**, B. Siciliano, F. Ficuciello, "*Human-Robot Interactive Framework with Remote Center of Motion and Virtual Fixtures Contraint*", **in submission to** 19th International Symposium on Advances in Robot Kinematics

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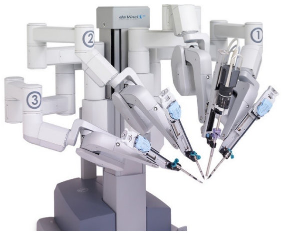
Vision-Based Dynamic Virtual Fixtures for Tools Collision Avoidance in Robotic Surgery

Problem Statement:

- Surgical tools can collide and create serious damage to human tissues



Proposed Solution:

Surgical tools collision avoidance method:
- Forbidden Region Virtual Fixtures (FRVF)
- A marker-less tool tracking method using deep neural network
- Extended Kalman Filter (EKF) for tool pose estimation ensures robust application of VF

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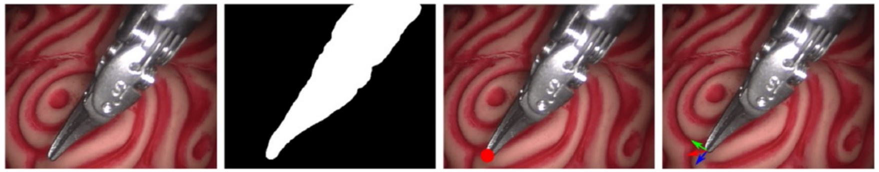
Vision-Based Dynamic Virtual Fixtures for Tools Collision Avoidance in Robotic Surgery

Solution:

- Tool Segmentation and 3D Reconstruction
- Extended Kalman Filter for pose tracking
- Kinematics and Vision data fusion



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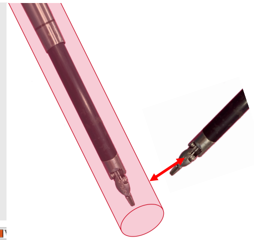
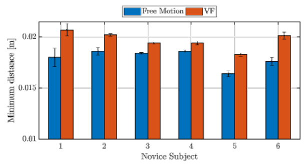
Vision-Based Dynamic Virtual Fixtures for Tools Collision Avoidance in Robotic Surgery

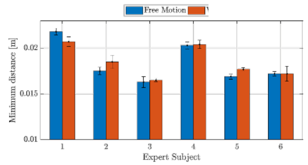
- FRVF defined as the swept surface along the tool axis
- A constraint enforcement is defined

$$f_{vf}(\tilde{x}, \dot{\tilde{x}}) = -K_{vf}\tilde{x} - D_{vf}\dot{\tilde{x}}$$

- Human Subject Study







Rocco Moccia, Cristina Iacono, Bruno Siciliano and Fanny Ficuciello, "Vision-based dynamic virtual fixtures for tools collision avoidance in robotic surgery". IEEE Robotics and Automation Letters. 2020 Jan 28;5(2):1650-5.

Products

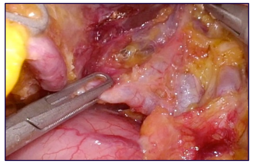
J1	R. Moccia, **C. Iacono**, B. Siciliano and F. Ficuciello, "*Vision-Based Dynamic Virtual Fixtures for Tools Collision Avoidance in Robotic Surgery*" in IEEE Robotics and Automation Letters, vol. 5, no. 2, pp. 1650-1655, April 2020.
W1	**C. Iacono**, R. Moccia, B. Siciliano, F. Ficuciello, "*Vision-Based Dynamic Virtual Fixtures for Tools Collision Avoidance in MIRS*", 10th Joint Workshop on New Technologies for Computer/Robot Assisted Surgery, Barcelona, Spain, September 28-30, 2020.
W2	**C. Iacono**, R. Moccia, B. Siciliano, F. Ficuciello, "*Forbidden Region Virtual Fixtures for Surgical Tools Collision Avoidance*", Proc. Institute for Robotics and Intelligent Machine Conference, Rome, Italy, October 18-20, 2020.

Localization of the biliary tract in laparoscopic images

Laparoscopic Cholecystectomy:

Advantages: faster recovery and better cosmetic results

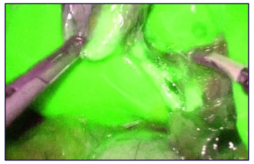
Disadvantages: higher risk of bile duct injury



Indocyanine green (ICG):

Advantage: Enhanced intraoperative visualization of the bile duct

Disadvantage: Challenging to see all the other anatomical structures



Objective:

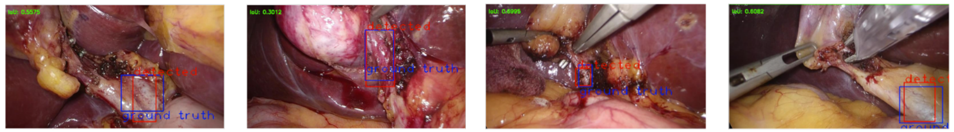
Help the surgeon to better visualize the biliary tract without the use of ICG

Localization of the biliary tract in laparoscopic images

Proposed Solution:

- You Only Look Once (YOLO) on laparoscopic images to localize the biliary duct.
- Construction and annotation of an image database to train the deep learning algorithm
- Average IoU of 67%

	Total Frames	*Training*	*Test*
Patient 1	142	15	15
Patient 2	171	34	14
Patient 3	219	-	39
Patient 4	152	74	20
Patient 5	48	5	5
Patient 6	144	-	29
Patient 7	168	14	10
Patient 8	89	18	10
Patient 9	153	14	10
Patient 10	73	20	10
Patient 11	27	14	10
Patient 12	135	-	19



(a) Patient 3. (b) Patient 4. (c) Patient 6. (d) Patient 12.

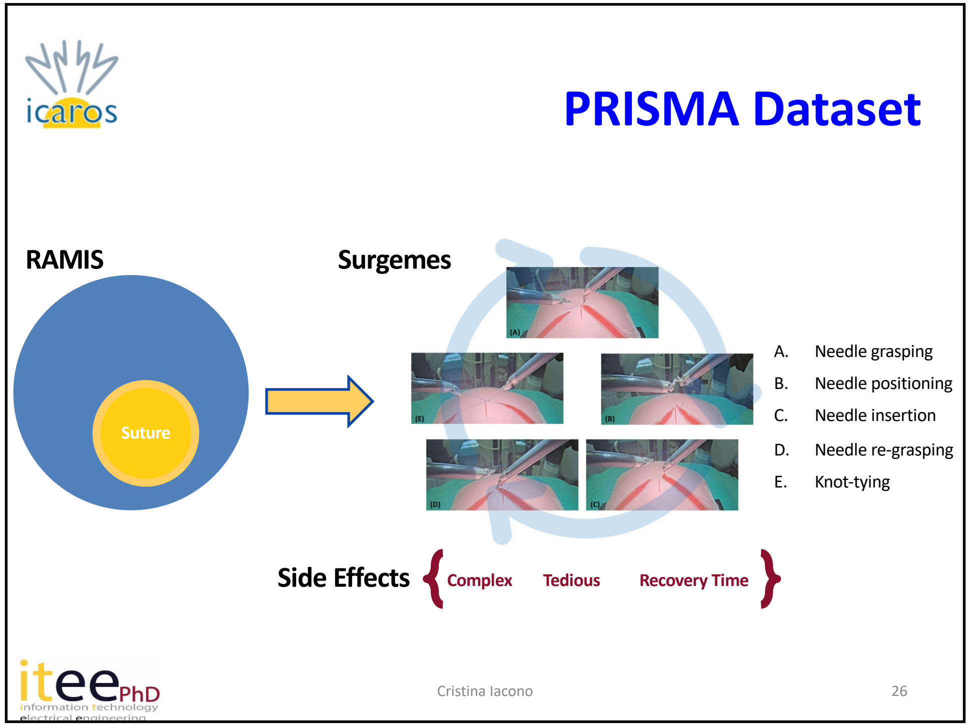
Products

W1	**C. Iacono**, S. Moccia, A. Marzullo, E. De Momi, U. Bracale, F. Ficuciello "*Deep learning-based localization of the biliary tract in laparoscopic images acquired during surgical robotic procedures*", Italian Institute of Robotics and Intelligent Machines (I-RIM) 3D 2021, October 8-9, 2021.
W2	**C. Iacono**, S. Moccia, A. Marzullo, E. De Momi, F. Ficuciello, U. Bracale, "*Deep learning-based localization of the biliary tract on white-light images acquired during laparoscopic cholecystectomy*", 11th Joint Workshop on New Technologies for Computer/Robot Assisted Surgery, Naples, Italy, April 25-27, 2022.

Worcester Polytechnic Institute

Work:

- Recreation of the dVRK WPI setup in ICAROS:
  - Monitor
  - SUJ calibration
- Designed User Study to collect a suturing dataset:
  - Training
  - Compliance
  - Experiment
  - Survey
- Worked on the 2021/2022 AccelNet Surgical Robotics Challenge:
  - Grasp needle and drive through tissue
  - Learning from demonstration


icaros
PRISMA Dataset
RAMIS
Suture
Surgemes
A. Needle grasping
B. Needle positioning
C. Needle insertion
D. Needle re-grasping
E. Knot-tying
Side Effects
Complex
Tedious
Recovery Time
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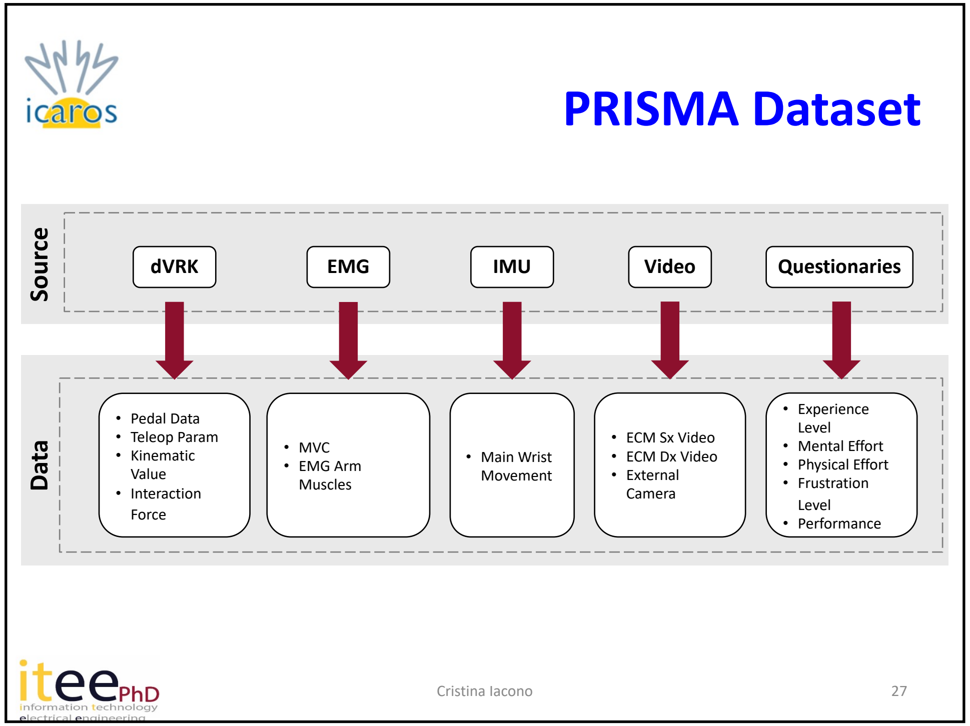
icaros
PRISMA Dataset
Source
dVRK
EMG
IMU
Video
Questionaries
Data
• Pedal Data
• Teleop Param
• Kinematic Value
• Interaction Force
• MVC
• EMG Arm Muscles
• Main Wrist Movement
• ECM Sx Video
• ECM Dx Video
• External Camera
• Experience Level
• Mental Effort
• Physical Effort
• Frustration Level
• Performance
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Prisma Dataset

Prisma Dataset:

- **Goal:** Collect data to automatize the Suture Task
- **Data:** 33 Kinematic variables, Video from ECM and External Camera, EMG and IMU from the Surgeon and Surgeon's mental and physical fatigue recorded by questionaries
- **Task:** Discontinued Suture
- **Gestures:** 5 Suture Step Classification

JIGSAWS:

- **Goal:** Collect Data to train novice surgeon
- **Data:** 19 Kinematic variables and Video from ECM
- **Task:** Continue Suture
- **Gestures:** 10 Suture Step Classification

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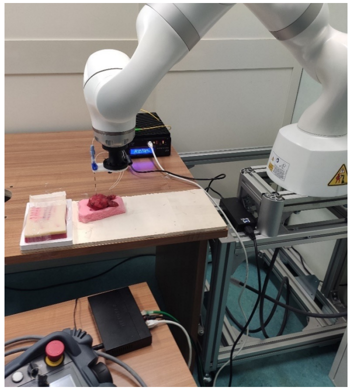
Ex vivo testing of a miniaturized probe for prostate tissue characterization

Problem:

Characterization of mechanical properties of insane and healthy prostate tissues

Objective:

Testing on phantom tissues and ex-vivo tissues a miniaturized probe based on optical fiber



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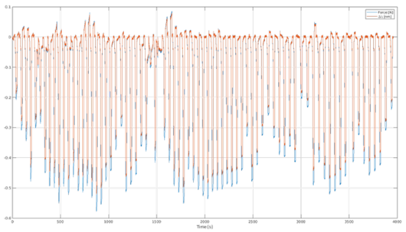
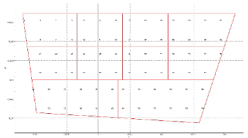
Ex vivo testing of a miniaturized probe for prostate tissue characterization

Results:

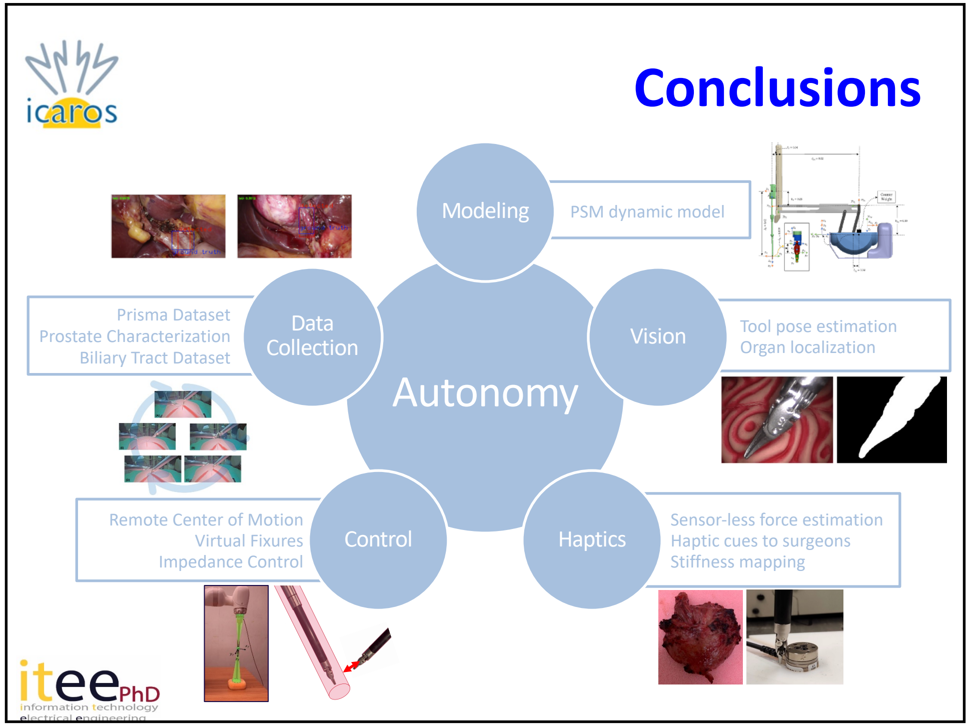
Creation of a dataset of elasticity measurements of prostate





Other Products

W1	M. Caianiello, **C. Iacono**, A. Imperato, F. Ficuciello, "*Deep Deterministic Policy Gradient from Success: A New Approach for Robot-Assisted Suturing*", Proc. Institute for Robotics and Intelligent Machine Conference, Rome, Italy, October 20-22, 2023.
C1	M. Caianiello, **C. Iacono**, A. Imperato, F. Ficuciello, "*Exploring the Use of Deep Reinforcement Learning Algorithms for Wound-Approaching Trajectories in Robot-Assisted Minimally Invasive Surgery*", 2023 21th International Conference on Advanced Robotics (ICAR), Abu Dhabi, United Arab Emirates, December 2023


Conclusions
Modeling
PSM dynamic model
Data Collection
Prisma Dataset
Prostate Characterization
Biliary Tract Dataset
Autonomy
Vision
Tool pose estimation
Organ localization
Control
Remote Center of Motion
Virtual Fixures
Impedance Control
Haptics
Sensor-less force estimation
Haptic cues to surgeons
Stiffness mapping
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Thank you for your attention!
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