Rocco Moccia

Tutor: Prof. Bruno Siciliano – co-Tutor: Prof. Fanny Ficuciello

XXXIII Cycle - III year presentation

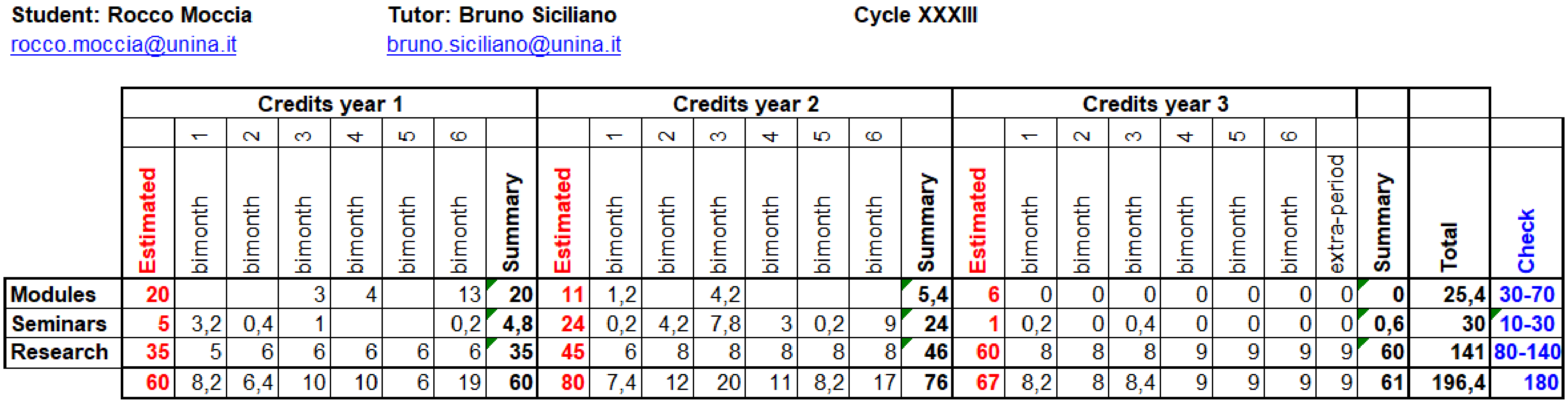
Vision-based Autonomous Control in Robotic Surgery

Università degli Studi di Napoli Federico II

Background

- **M. Sc. Degree:** Mechanical Engineering from Sapienza, Università di Roma
- **Team:** ICAROS and PRISMA Lab
- **Collaboration:**
  - University of Leeds (UK)
  - Medical Micro Instruments, MMI S.p.A (Italy)
  - INRIA Strasbourg (France)
- **Supervisors:** Prof. Bruno Siciliano and Prof. Fanny Ficuciello
- **Fellowship:** PON

Credits



Student: Rocco Moccia **Tutor: Bruno Siciliano** **Cycle XXXIII**

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	Credits year 1								Credits year 2								Credits year 3										
		1	2	3	4	5	6			1	2	3	4	5	6			1	2	3	4	5	6				
	Estimated	bimonth	bimonth	bimonth	bimonth	bimonth	bimonth	**Summary**	**Estimated**	bimonth	bimonth	bimonth	bimonth	bimonth	bimonth	**Summary**	**Estimated**	bimonth	bimonth	bimonth	bimonth	bimonth	bimonth	extra-period	**Summary**	**Total**	**Check**
Modules	**20**			3	4		13	**20**	**11**	1,2		4,2				**5,4**	**6**	0	0	0	0	0	0	0	**0**	**25,4**	**30-70**
Seminars	**5**	3,2	0,4	1			0,2	**4,8**	**24**	0,2	4,2	7,8	3	0,2	9	**24**	**1**	0,2	0	0,4	0	0	0	0	**0,6**	**30**	**10-30**
Research	**35**	5	6	6	6	6	6	**35**	**45**	6	8	8	8	8	8	**46**	**60**	8	8	8	9	9	9	9	**60**	**141**	**80-140**
	60	8,2	6,4	10	10	6	19	**60**	**80**	7,4	12	20	11	8,2	17	**76**	**67**	8,2	8	8,4	9	9	9	9	**61**	**196,4**	**180**

Credits

Year	Lecture/Activity	Type	Credits	Certification	Notes
	MODULES				
1	Green Economy and Management in Engineering projects	External Module	3	x	
1	Summer School on Control of Surgical Robots (COSUR 2018)	Doctoral School	4	x	
1	Image Processing For Computer Vision	MS Module	9	x	
1	Geometric Theory of Soft Robots	External Module	4	x	
2	Data Science and Optimization	Ad Hoc Module	1,2	x	
2	Machine Learning	Ad Hoc Module	4,2	x	
	SEMINARS				
1	EIT-Health Matchmaking Event 2018	Conference	3,2	x	
1	The Age of Human-Robot Collaboration	Seminar	0,4	x	
1	IBMQ: Building the First Universal Quantum Computers for Business and Science	Seminar	0,8	x	
1	How Does Mathworks Accelerate the Pace of Engineering and Science?	Seminar	0,2	x	
1	Domains of Attraction and Manifolds in Gear Model	Seminar	0,2	x	
2	Issues in Robotic Manipulation of Deformable Objects	Seminar	0,2	x	
2	Research work in active perception and robot interactive lab in IIT	Seminar	0,2	x	
2	Robots in Medical applications: an overview of the current Medical Robotics market from the industry's point of view	Seminar	0,4	x	
2	9th Joint Workshop on New Technologies for Computer/Robot Assisted Surgery	Conference	3,6	x	
2	Presentazione ADI: vittorie, sfide, obiettivi	Seminar	0,2	x	
2	Control of Multi-Robot systems: from rendez-vous to long-duration autonomy	Seminar	0,2	x	
2	The Hamlyn Symposium on Medical Robotics 2019	Conference	7,2	x	
2	PID Passivity-based Control: Application to Energy and Mechanical Systems	Seminar	0,2	x	
2	SIDRA 2019 PhD Summer School	Doctoral School	3	x	
2	Innovation in Medical Robotics and the human-centred paradigm	Seminar	0,2	x	
2	2019 IEEE/RSJ International Conference on Intelligent Robots and Systems	Conference	9	x	
3	Numerical methods for modeling, simulation and control for soft robots or robots in interaction with deformable environment	Seminar	0,2	x	
3	Exploring autonomy in robotic colonoscopy	Seminar	0,4	x	

Company and Abroad Periods

- **STORM Lab – University of Leeds:** School of Electronic and Electrical Engineering, Leeds, LS2 9JT (UK)

  Jun. 2020 – Mar. 2021 (from home)
- **Medical Micro Instruments, S.p.A:** via del Paduletto 10A, 56011, Calci (PI), Italy

  Nov. 2019 – Mar. 2020 (on site)

  Mar. 2020 – May 2020 (from home)
- **MIMESIS Team – INRIA Strasbourg:** 1, place de l’Hôpital 67000, Strasbourg (France)

  Jul. 2018

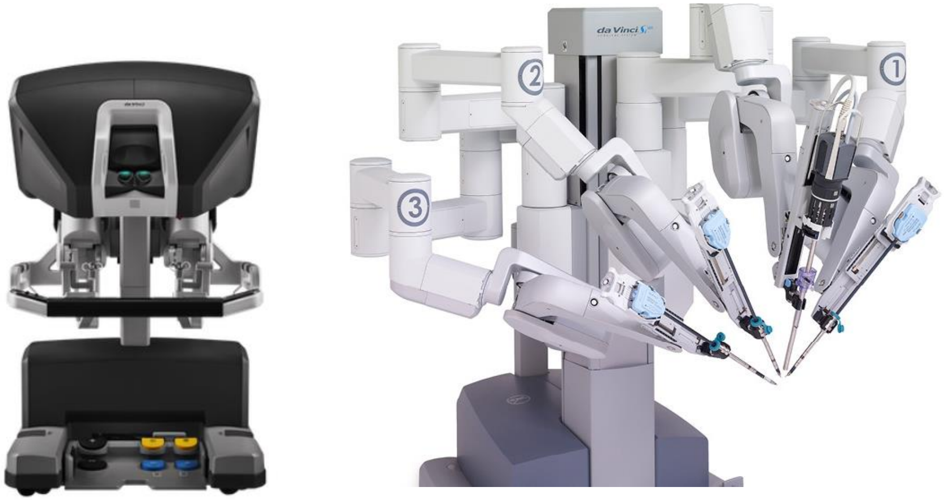
Robotic Surgery Background

Robots completely changed surgical procedures, introducing:

- Enhanced dexterity
- Motion scaling
- Tremor filtering

Minimally invasive Surgery and **Microsurgery** are the most suitable surgical fields in which robots can produce a significant contribute

Robotic Surgery Background



da Vinci® Surgical System:

- Widely used **robotic** system for robot-assisted **laparoscopic** procedures

Symani® Surgical System:

- Most advanced **surgical robot** for complex **microsurgical** procedures

Robotic Surgery Background

Levels of Autonomy for **Surgical Robots**:

⓪ Operator performs all tasks including monitoring, generating performance options, selecting the option to perform (decision-making), and executing the decision made.

No autonomy

① Operator maintains continuous control of the system while the robot provides certain assistance.

Robot assistance

② Operator maintains discrete control of the system, and the robot can perform certain operator-initiated tasks automatically.

Task autonomy

③ Operator selects and approves a surgical plan, and the robot performs the procedure automatically but with close surgical oversight by human.

Conditional autonomy

④ Robot is able to make decisions but under the supervision of a qualified operator.

High autonomy

⑤ No human needs to be in the loop, and the robot can perform an entire surgery.

Full automation

Goal, motivation and approach

The **goal** of this thesis is to create reliable solutions to enhance the quality of intervention in surgical robotic procedures

The main **motivation** is to overcome robot's limits in critical tasks whose success still relies on surgeon's abilities

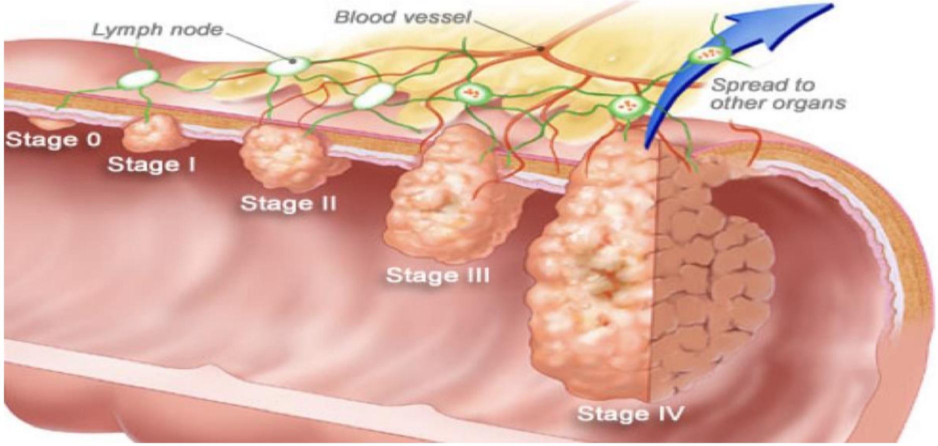
Two **approaches** are used simultaneously:

1. introduce **advanced control** methods, using **shared control** paradigms and laying the foundations for full **autonomous** surgical procedures
2. propose **computer vision** algorithms, adopting traditional and ML approaches, that represent a valid support for novel control methods in surgical robotics

Vision-based VF for polyp dissection

Problem: Colorectal polyp dissection requires very accurate detection of region of interest and precise cutting

Solution: vision-based method to assist the surgeon by means of a shared control approach (Virtual Fixtures)



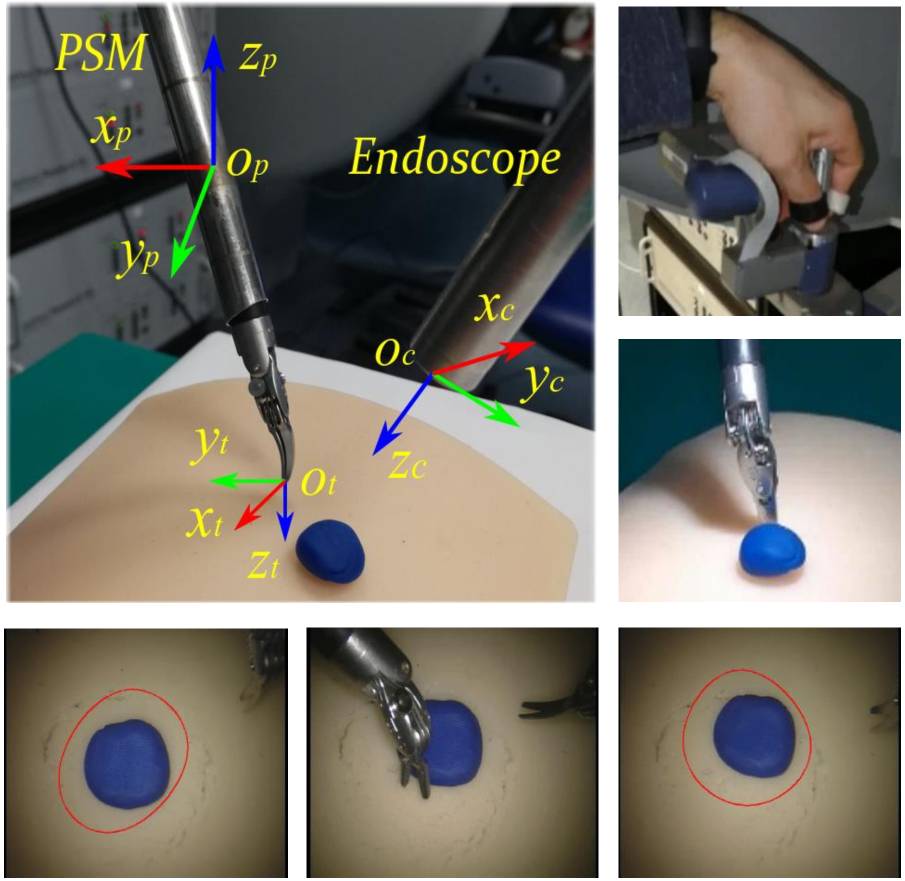
Results: high-quality dissection

R. Moccia et al. ”Vision-based Virtual Fixtures Generation for Robotic-Assisted Polyp Dissection Procedures”, IEEE/RSJ IROS 2019

Vision-based VF for polyp dissection

Method:

- The optimal dissection path using visual computation of control points
- Virtual Fixtures ensure realization of the planned path
- Haptic guidance implementation through impedance control



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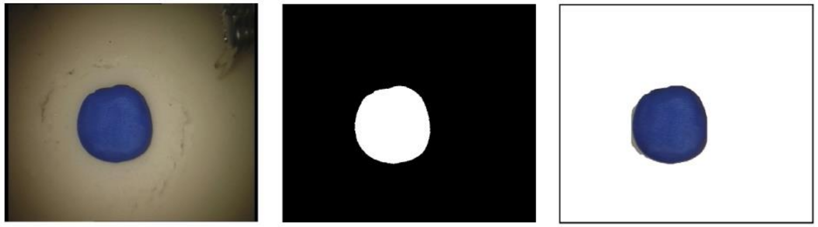
Vision-based VF for polyp dissection

Segmentation: Watershed transformation and *Grabcut* method



Cutting Path: formulated through a B-Spline curve

$$\Gamma(s) = \sum_{i=0}^{n} N_{i,k}(s)\, p_i$$

Attractive Force: imposed on VF path

$$f_{VF} = K_p(x_d - x) - K_d \dot{x}$$

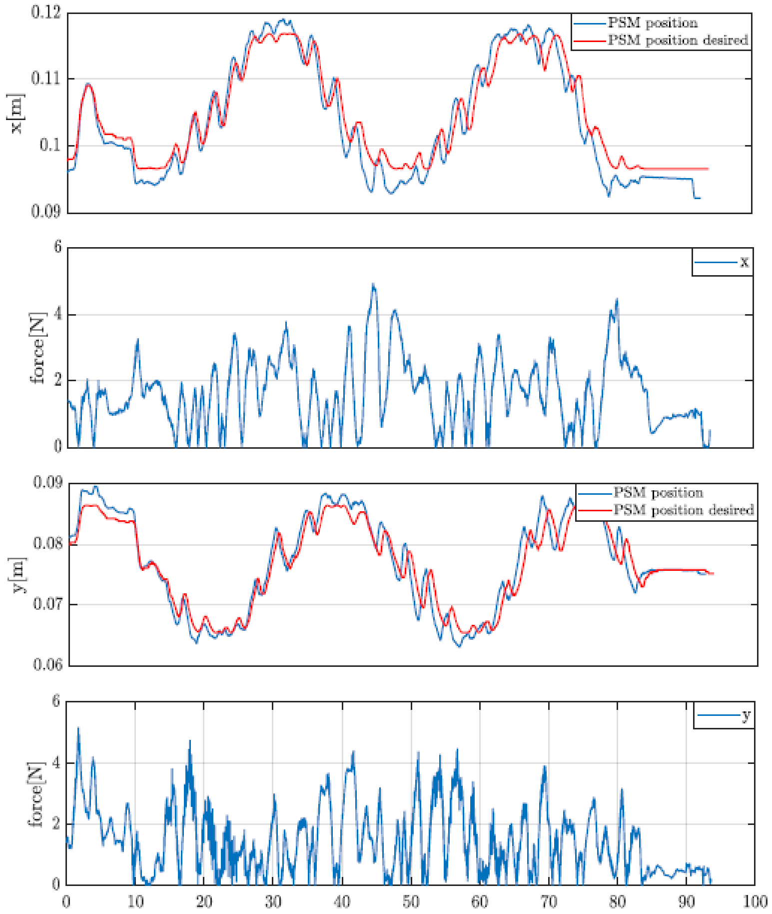
$$M\ddot{\tilde{x}} + D\dot{\tilde{x}} = f_h + f_{VF}(\cdot)$$

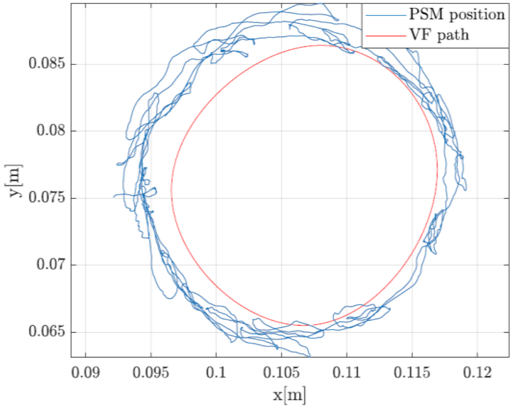
R. Moccia et al. ”Vision-based Virtual Fixtures Generation for Robotic-Assisted Polyp Dissection Procedures”, IEEE/RSJ IROS 2019

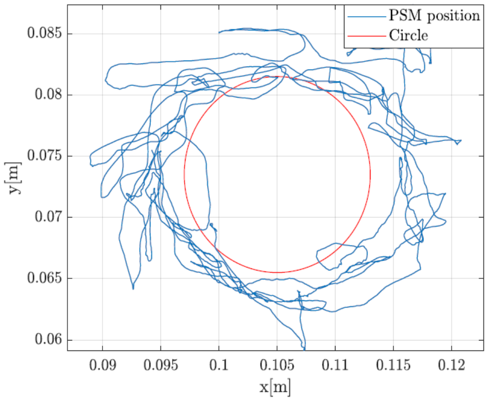
Vision-based VF for polyp dissection

Results:

- Optimal path autonomously adapted to environmental changes
- Improved accuracy and precision of intervention







R. Moccia et al. "Vision-based Virtual Fixtures Generation for Robotic-Assisted Polyp Dissection Procedures", IEEE/RSJ IROS 2019

Suturing Needle Tracking

Problem: Suturing represents a very difficult procedure in Robotic Surgery

Solution: tracking of suturing needle to define the grasping pose optimizing the cost of robot joint limits and singularities

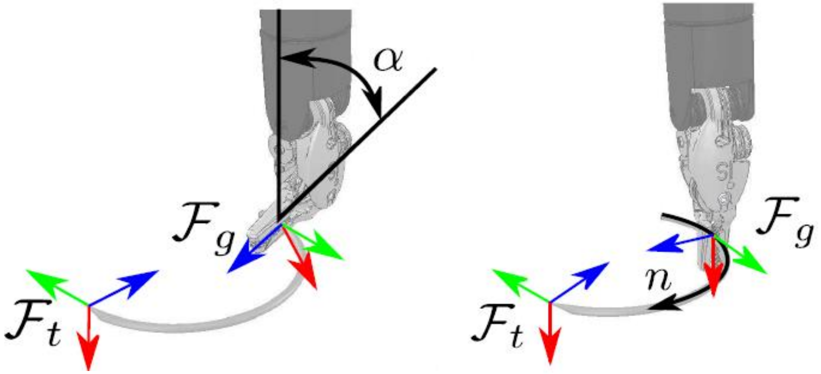
Results: continuous suturing avoiding tedious interruptions

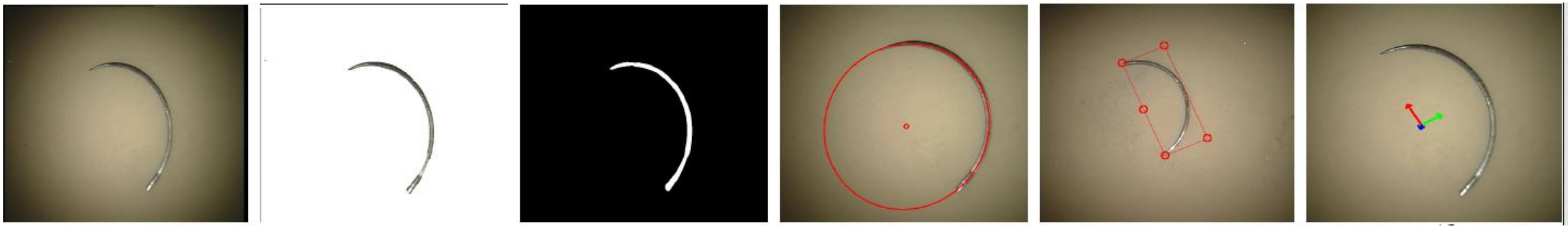
R. Moccia et al. ”Haptic-guided shared control for needle grasping optimization in minimally invasive robotic surgery”, Hamlyn Symposium Workshop 2019

Suturing Needle Tracking

Method:

- Vision-based detection and tracking of suturing needle
- Grasping optimization avoids joint limits and singularities along the suturing path
- Haptic guidance suggests the optimal grasp to the surgeon





R. Moccia et al. ”Haptic-guided shared control for needle grasping optimization in minimally invasive robotic surgery”, Hamlyn Symposium Workshop 2019

Suturing Needle Tracking

Cost Function:

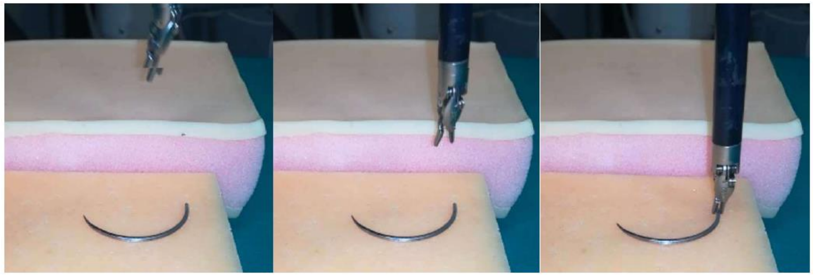
$$h\left(\hat{\boldsymbol{q}}_g\right) = h_j\left(\hat{\boldsymbol{q}}_g\right) + h_s\left(\hat{\boldsymbol{q}}_g\right)$$

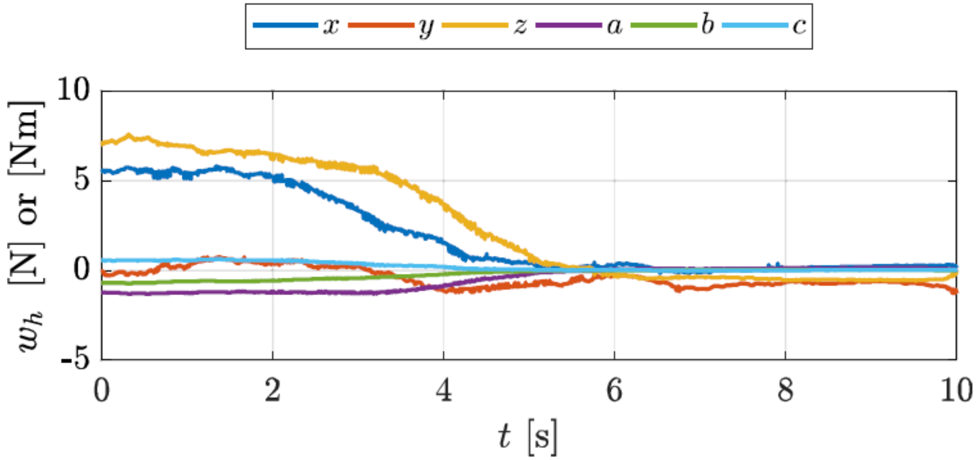
$$\mathcal{H}\left(\boldsymbol{z}\right) = \int_0^{s^\star} h\left(\hat{\boldsymbol{q}}_g\left(s, {}^r\boldsymbol{T}_g\right)\right) \mathrm{d}s = \int_0^{s^\star} h\left(\hat{\boldsymbol{q}}_g\left(s, \boldsymbol{z}\right)\right) \mathrm{d}s$$

$$\begin{aligned} \underset{z}{\text{minimize}} \quad & \mathcal{H}(\hat{\mathbf{q}}_g(\mathbf{z})) \\ \text{subject to} \quad & \mathbf{z}^- \leq \mathbf{z} \leq \mathbf{z}^+ \end{aligned}$$

Results:

- post-grasp movements during the suturing task are free from constraints





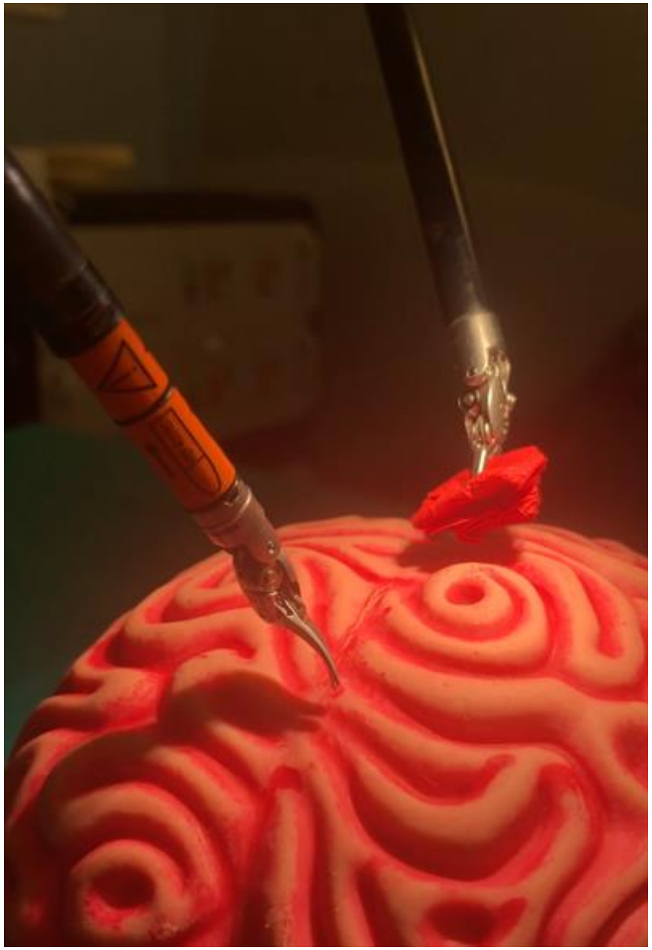
R. Moccia et al. ”Haptic-guided shared control for needle grasping optimization in minimally invasive robotic surgery”, Hamlyn Symposium Workshop 2019

Vision-based VF for collision avoidance

Problem: In robotic surgery surgical tools could collide, creating serious damage to the robot or human tissues

Solution: Tool collision avoided by rendering a repulsive force to surgeon

Results: human-subject study



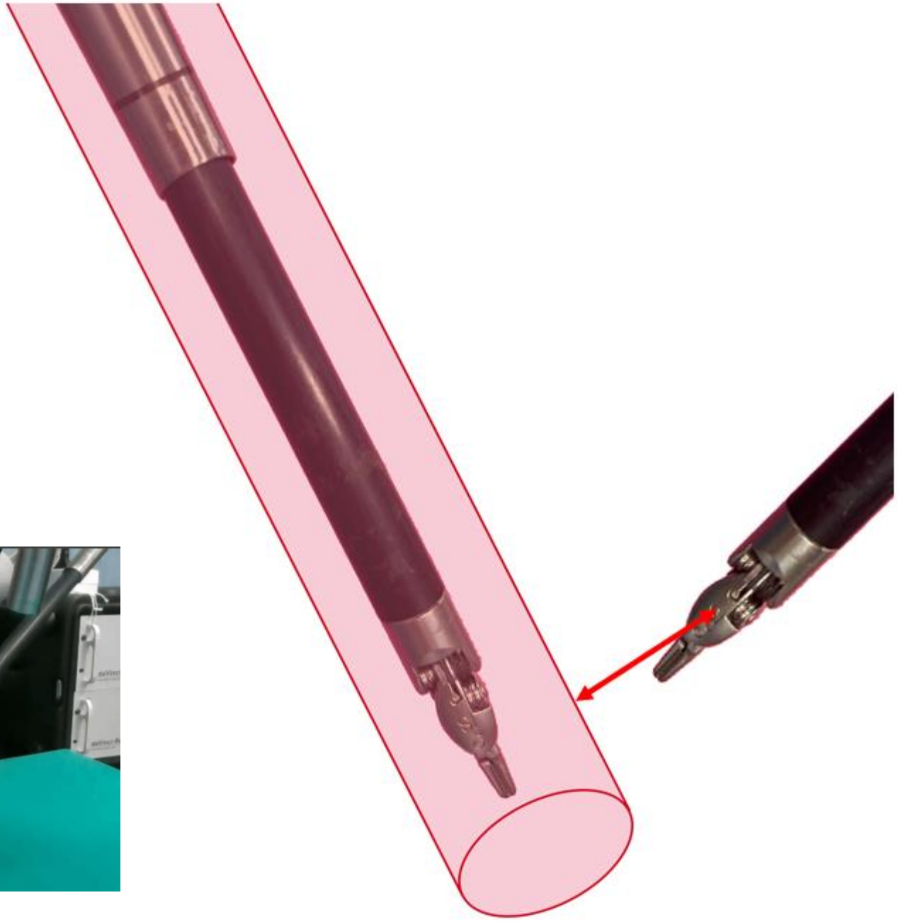
R. Moccia et al. "Vision-based Dynamic Virtual Fixtures for Tools Collision Avoidance in Robotic Surgery", IEEE Robotics and Automation Letters 2020

Vision-based VF for collision avoidance

Method:

- Marker-less surgical tool tracking using EKF coupling vision and kinematics information
- Shared control (VF) and haptic guidance method

$$\boldsymbol{f}_{vf}(\tilde{\boldsymbol{x}}, \dot{\tilde{\boldsymbol{x}}}) = -\boldsymbol{K}_{vf}\tilde{\boldsymbol{x}} - \boldsymbol{D}_{vf}\dot{\tilde{\boldsymbol{x}}}$$



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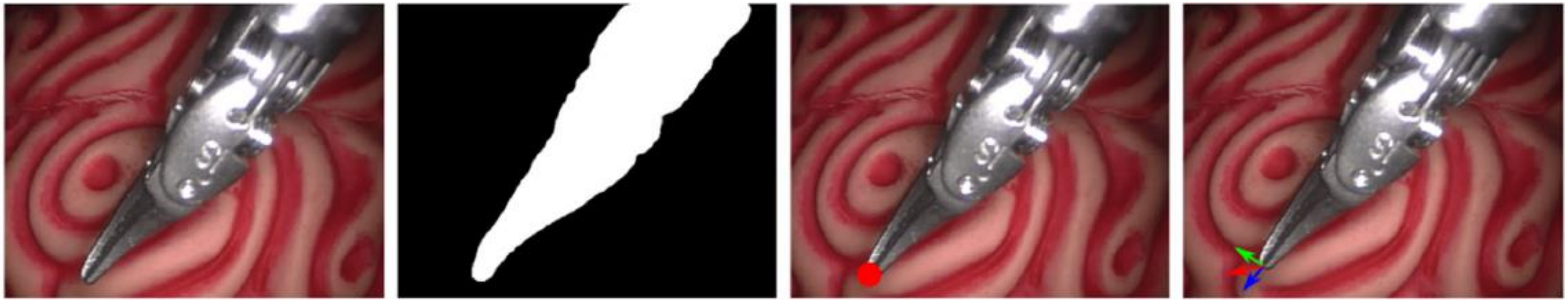
Vision-based VF for collision avoidance

Tool segmentation:

- Deep learning solution for instrument segmentation, using fully convolutional neural network
- 3D position of PSM tip is reconstructed by using triangulation with direct linear transformation, while orientation is computed solving *PnP* problem



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Vision-based VF for collision avoidance

Tool tracking:

- Process dynamics:

$$\begin{cases} \dot{\boldsymbol{p}}_t = \boldsymbol{v}_g + \boldsymbol{S}\left(\boldsymbol{\omega}_g\right)\boldsymbol{r}_{gt} + \boldsymbol{n}_p \\ \dot{\boldsymbol{q}}_t = \dfrac{1}{2}\boldsymbol{\Omega}\left(\boldsymbol{\omega}_g\right)\boldsymbol{q}_t + \boldsymbol{n}_q \end{cases}$$

- Measurement model:

$$\boldsymbol{y} = \boldsymbol{\zeta} + \boldsymbol{m} \qquad \boldsymbol{F} = \begin{bmatrix} \boldsymbol{S}\left(\boldsymbol{\omega}_g\right) & \boldsymbol{O}_3 \\ \boldsymbol{O}_3 & \boldsymbol{S}\left(\boldsymbol{\omega}_g\right) \end{bmatrix} \qquad \boldsymbol{H} = \begin{bmatrix} \boldsymbol{I}_3 & \boldsymbol{O}_3 \\ \boldsymbol{O}_3 & \boldsymbol{I}_3 \end{bmatrix}$$

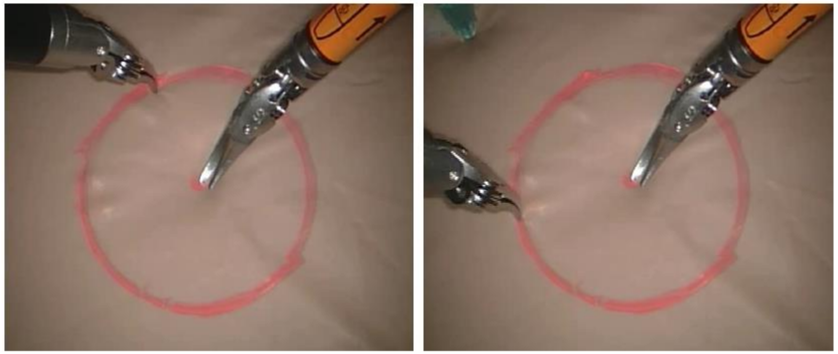
- The output of the EKF provides current pose of tool end-effector with respect to robot base frame

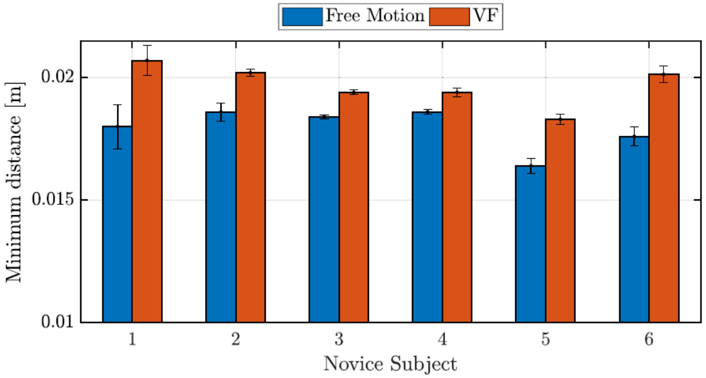
R. Moccia et al. ”Vision-based Dynamic Virtual Fixtures for Tools Collision Avoidance in Robotic Surgery”, IEEE Robotics and Automation Letters 2020

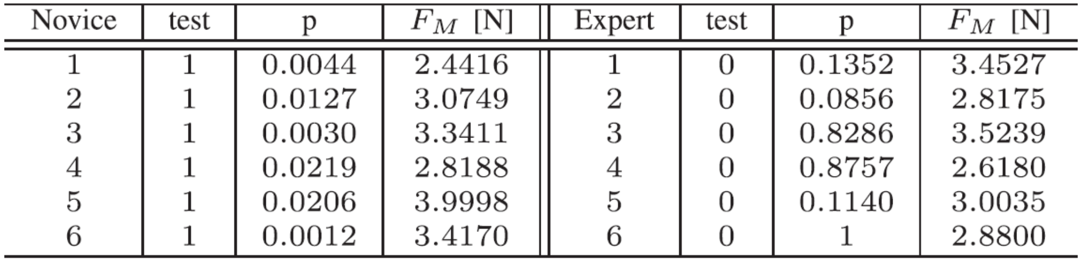
Vision-based VF for collision avoidance

Experimental validation:

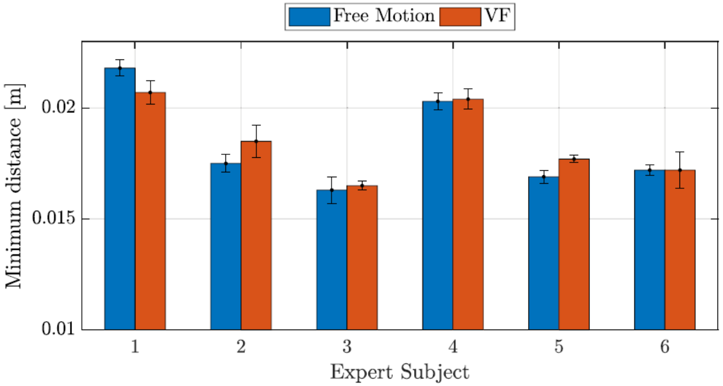
- User-study involving novice and expert surgeons







Novice	test	p	F_M [N]	Expert	test	p	F_M [N]
1	1	0.0044	2.4416	1	0	0.1352	3.4527
2	1	0.0127	3.0749	2	0	0.0856	2.8175
3	1	0.0030	3.3411	3	0	0.8286	3.5239
4	1	0.0219	2.8188	4	0	0.8757	2.6180
5	1	0.0206	3.9998	5	0	0.1140	3.0035
6	1	0.0012	3.4170	6	0	1	2.8800



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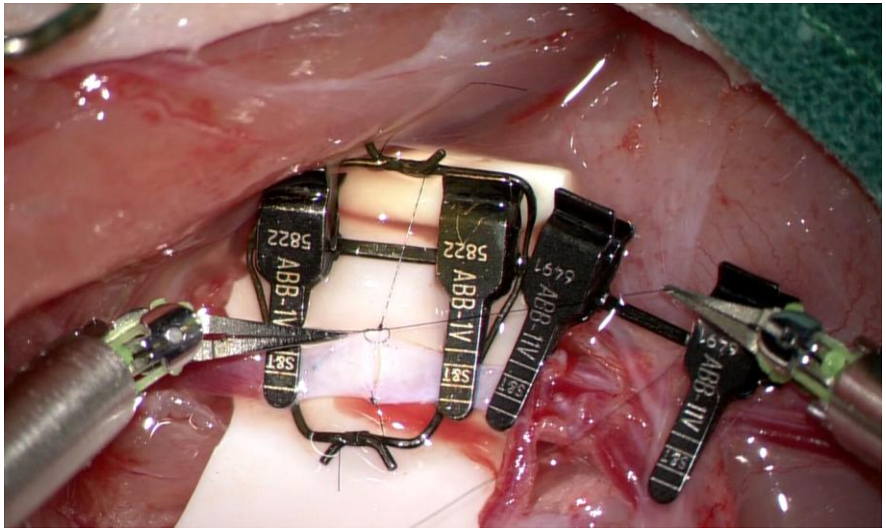
Multiple Task Execution using CBFs



Collaboration with

MMI
Microinstruments

Problem: Robot-aided surgical procedures involve a sequence of complex tasks

Solution: Executing tasks simultaneously gives the robot the ability to accomplish numerous assignments in safety conditions

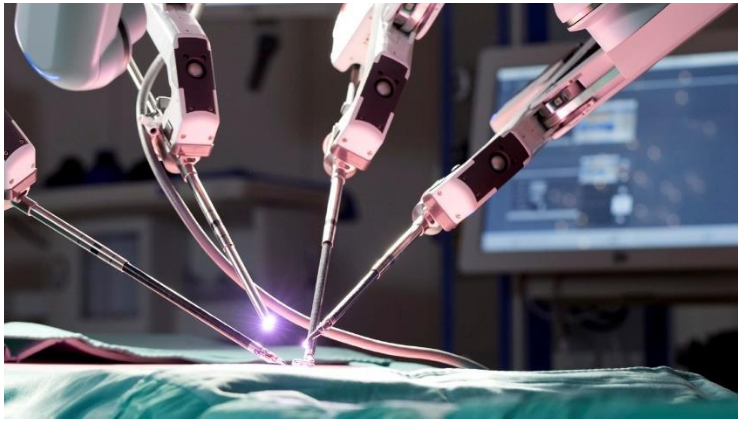
Results: Multiple task execution framework

R. Moccia et al. ”Multiple Tasks Execution using Control Barrier Functions in Surgical Robotics”, *in submission*

Multiple Task Execution using CBFs

Method:

- Optimization-based approach allows the accomplishment of multiple surgical tasks simultaneously
- Task definition and execution is achieved by means of Control Barrier Functions (CBFs)
- Dual Quaternion (DQ) algebra ensures a more efficient geometrical representation of surgical site



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Multiple Task Execution using CBFs

Robot Kinematics in DQ:

- Dual quaternion:

$$\mathcal{Q} \triangleq \{b + \varepsilon b' : b, b' \in \mathbb{Q}, \varepsilon^2 = 0, \varepsilon \neq 0\} \qquad \mathbb{Q} \triangleq \{\eta + \hat{i}\epsilon_x + \hat{j}\epsilon_y + \hat{k}\epsilon_z : \eta, \epsilon_x, \epsilon_y, \epsilon_z \in \mathbb{R}\}$$

- Rigid body pose in DQ:

$$\underline{\boldsymbol{x}} = \boldsymbol{r} + \varepsilon \frac{1}{2} \boldsymbol{p} \boldsymbol{r} \qquad \underline{\mathcal{S}} \triangleq \{\underline{\boldsymbol{x}} \in \mathbb{Q} : ||\underline{\boldsymbol{x}}|| = 1\} \text{ with } \underline{\boldsymbol{x}} \in \mathcal{Q},\, \boldsymbol{p} \in \mathbb{Q}_p \text{ and } \boldsymbol{r} \in \mathbb{S}^3$$

- Forward and differential kinematics:

$$\underline{\boldsymbol{x}}_{ee}^{base}(\boldsymbol{q}) = \underline{\boldsymbol{x}}_0^{base} \underline{\boldsymbol{x}}_1^0(\boldsymbol{q}_0) \underline{\boldsymbol{x}}_2^1(\boldsymbol{q}_1) \ldots \underline{\boldsymbol{x}}_n^{n-1}(\boldsymbol{q}_{n-1}) \underline{\boldsymbol{x}}_{ee}^n$$

$$\mathrm{vec}_8 \dot{\underline{\boldsymbol{x}}}(\boldsymbol{q}) = \boldsymbol{J}_{\underline{\boldsymbol{x}}}(\boldsymbol{q}) \dot{\boldsymbol{q}}$$

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Multiple Task Execution using CBFs

Task definition:

$$\mathcal{C} = \{\boldsymbol{\sigma} \in \mathcal{T} : \boldsymbol{h}(\boldsymbol{\sigma}, \boldsymbol{t}) \geq 0\}$$

$$\boldsymbol{h}(\boldsymbol{\sigma_d}, \boldsymbol{t}) = -\frac{1}{2}||\boldsymbol{e_\sigma}||^2, \quad \text{where} \quad \boldsymbol{e_\sigma} = \boldsymbol{\sigma} - \boldsymbol{\sigma_d}(\boldsymbol{t})$$

Task execution:

$$\sup_{\dot{\boldsymbol{q}} \in \mathcal{U}} \left\{ \boldsymbol{e}_{\boldsymbol{\sigma}}^T \dot{\boldsymbol{\sigma}}_d + \boldsymbol{e}_{\boldsymbol{\sigma}}^T \boldsymbol{J}_{\boldsymbol{\sigma}} \dot{\boldsymbol{q}} \right\} \geq -\gamma(\boldsymbol{h}(\boldsymbol{\sigma_d}))$$

$$\begin{aligned} \underset{\dot{\boldsymbol{q}}}{\text{minimize}} \quad & \|\dot{\boldsymbol{q}}\|^2 \\ \text{subject to} \quad & \boldsymbol{e}_{\boldsymbol{\sigma}}^T(\boldsymbol{t})\ \boldsymbol{J}_{\boldsymbol{\sigma}}(\boldsymbol{q})\dot{\boldsymbol{q}} \geq \\ & -\gamma(\boldsymbol{h}(\boldsymbol{\sigma_d}, \boldsymbol{t})) - \boldsymbol{e}_{\boldsymbol{\sigma}}^T(\boldsymbol{t})\dot{\boldsymbol{\sigma_d}}(\boldsymbol{t}) \end{aligned}$$

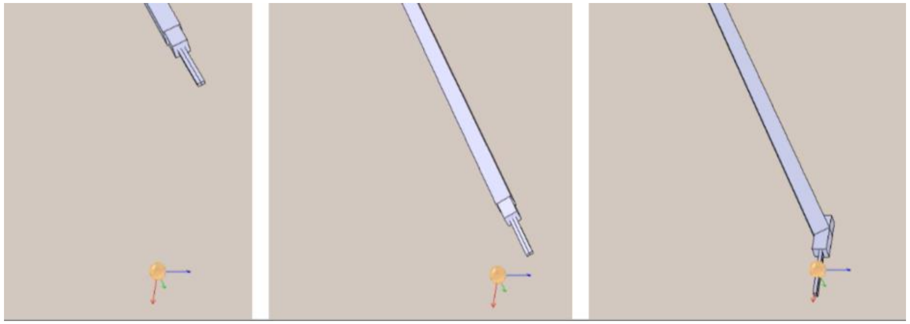
$$\begin{aligned} \underset{\dot{\boldsymbol{q}}}{\text{minimize}} \quad & \|\dot{\boldsymbol{q}}\|^2 + l\|\boldsymbol{\delta}\| \\ \text{subject to} \quad & \boldsymbol{A}(\boldsymbol{h}(\boldsymbol{\sigma}, \boldsymbol{t}))\dot{\boldsymbol{q}} \geq \boldsymbol{b}(\boldsymbol{h}(\boldsymbol{\sigma}, \boldsymbol{t})) \\ & \boldsymbol{K}(\boldsymbol{t})\boldsymbol{\delta} \geq 0 \end{aligned}$$

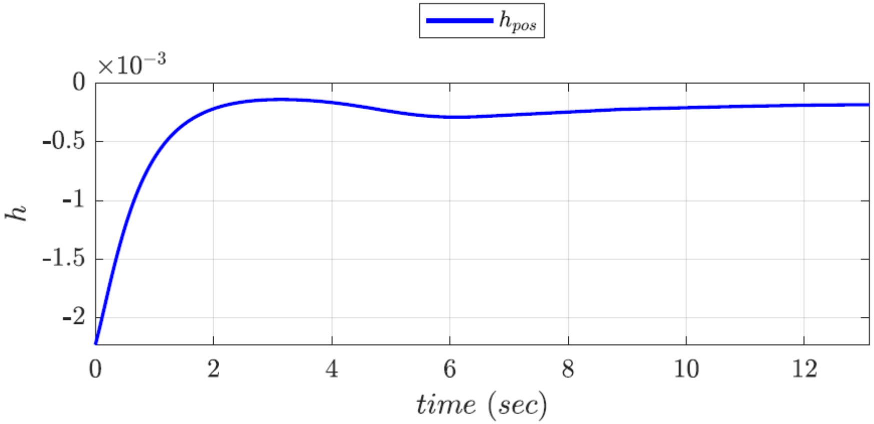
R. Moccia et al. ”Multiple Tasks Execution using Control Barrier Functions in Surgical Robotics”, *in submission*

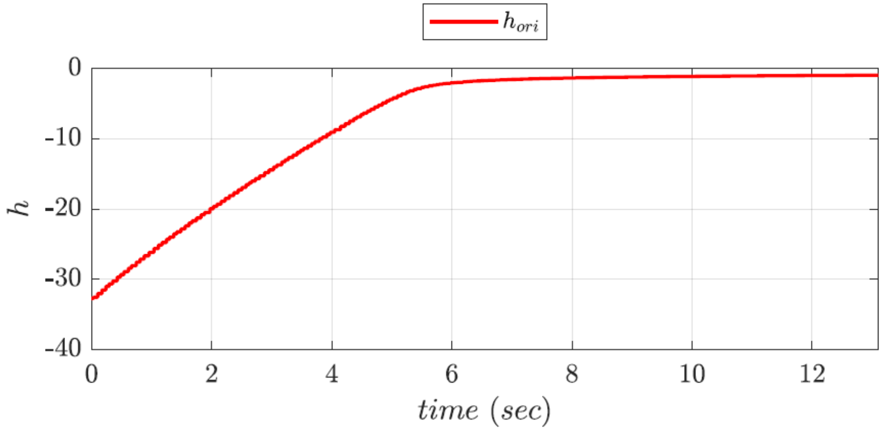
Multiple Task Execution using CBFs

Experimental Evaluation in simulation on Symani® Surgical System:

- Position and Orientation test







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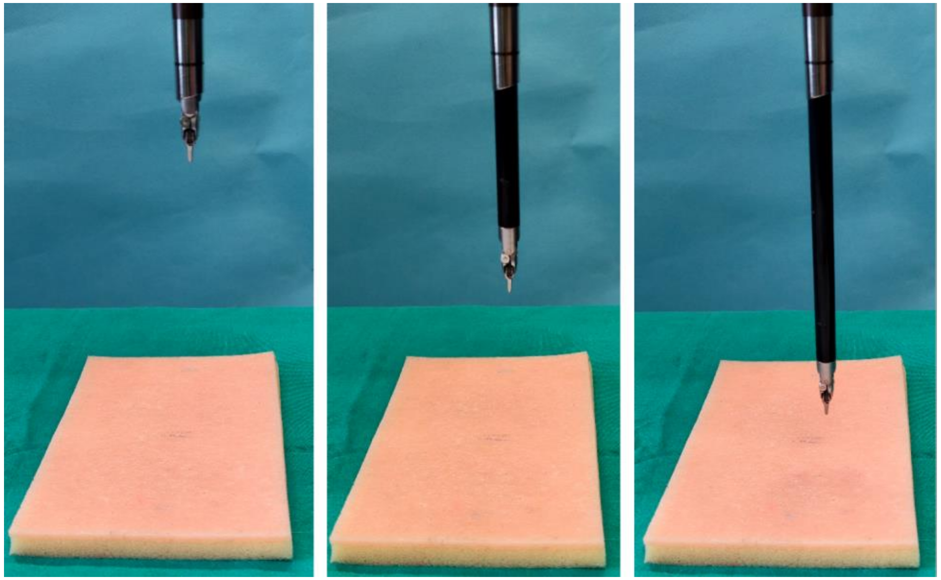
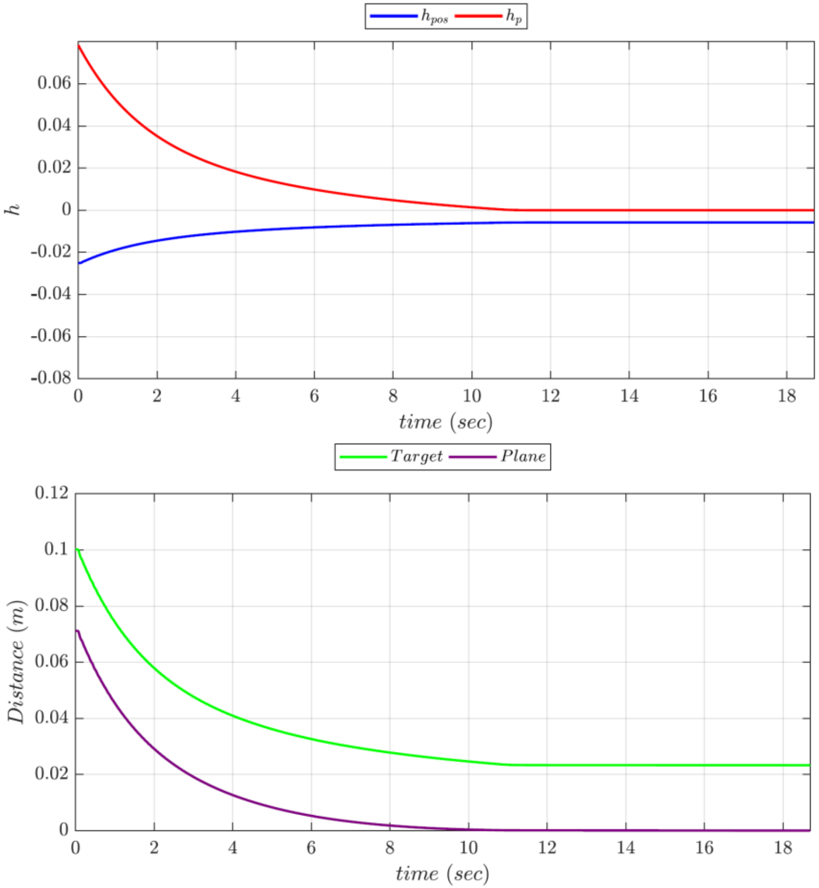
Multiple Task Execution using CBFs

Experimental Evaluation on dVRK Robot:

- Forbidden region avoidance test





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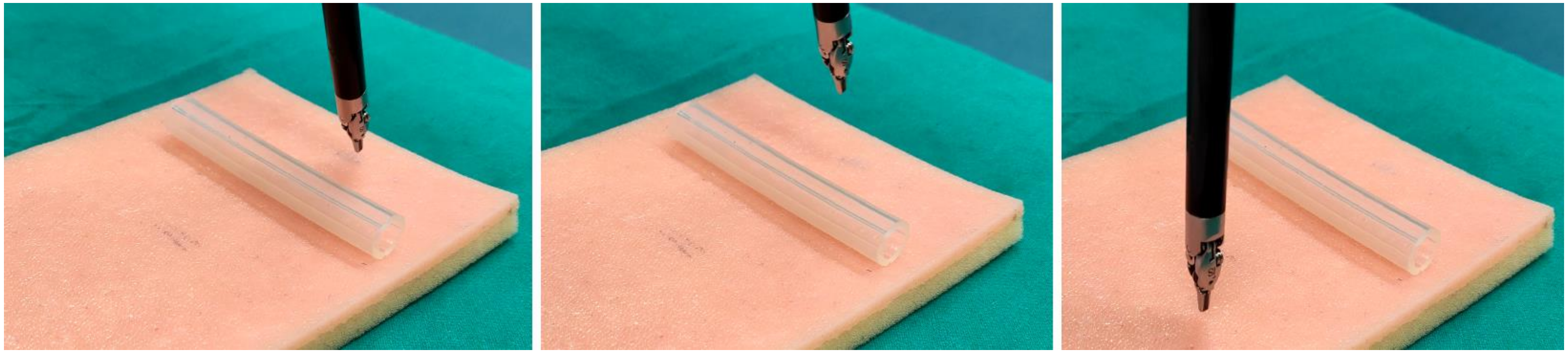
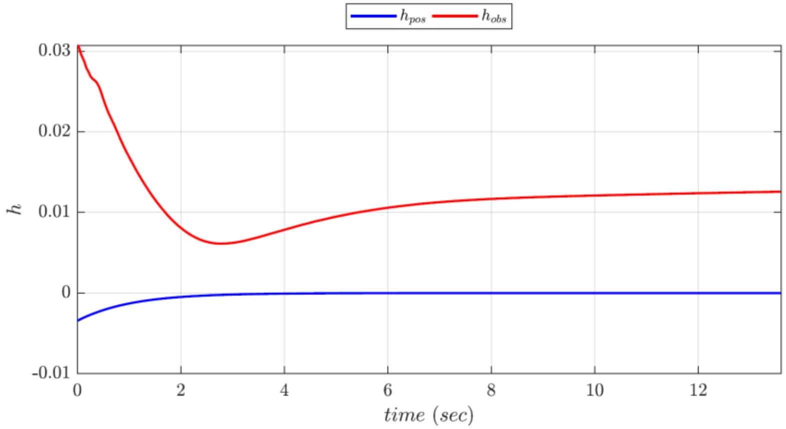
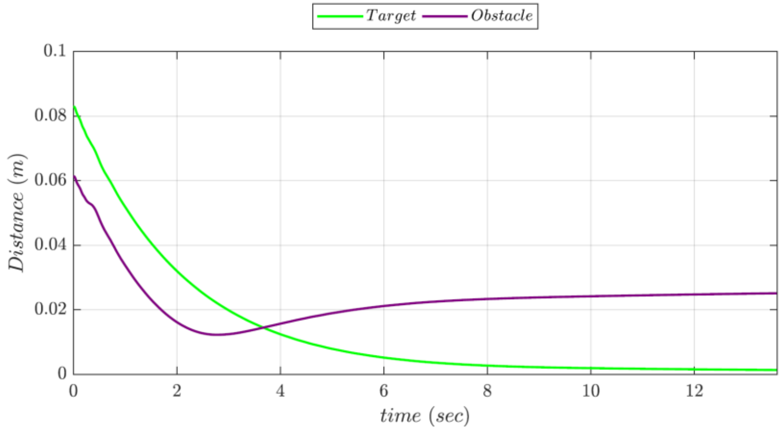
Multiple Task Execution using CBFs

Experimental Evaluation on dVRK Robot:

- Obstacle avoidance test



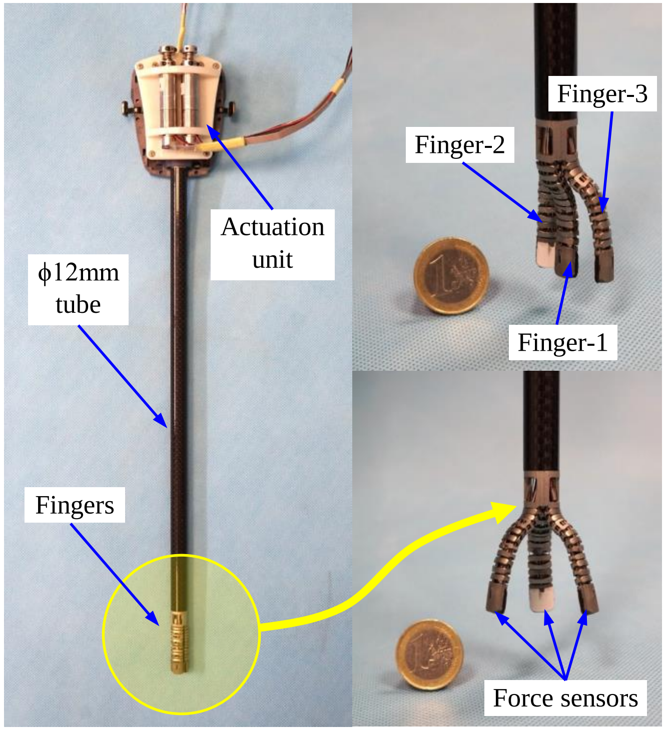


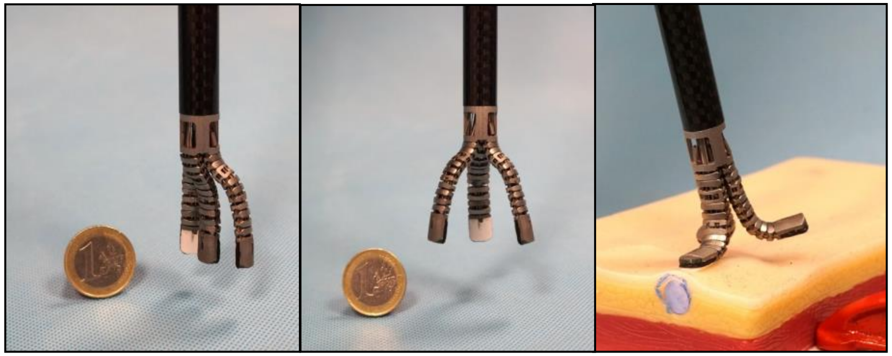


R. Moccia et al. ”Multiple Tasks Execution using Control Barrier Functions in Surgical Robotics”, *in submission*

Other Activities

Development of new surgical instruments (**MUSHA Hand II**): design and testing





H. Liu et al., ”The MUSHA Hand II: A Multi-Functional Hand for Robot-Assisted Laparoscopic Surgery”, IEEE/ASME Transactions on Mechatronics 2020

On-going Projects

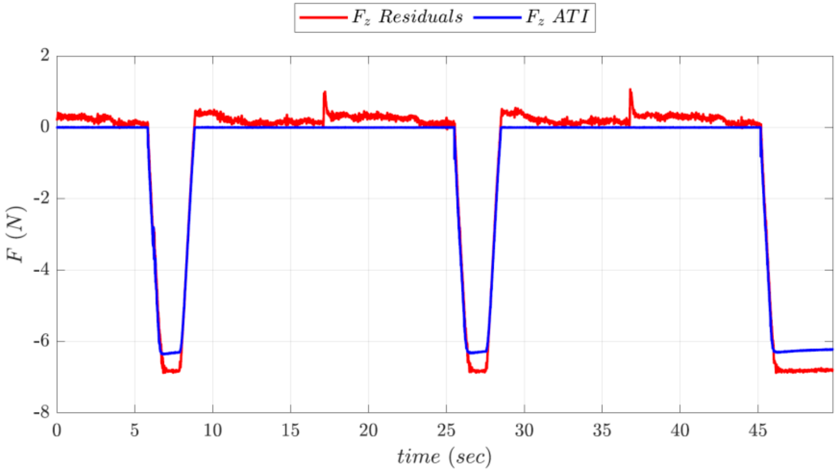
Problem: Ultrasound (US) scan of human organ requires accurate movements in safety-critical site

Solution: Autonomous US scan using da Vinci robot and novel probes

Method:

- dVRK dynamic model definition
- Sensor-less force contact estimation

Ultrasurge
Surgery Enabled By Ultrasonics



Collaboration with UNIVERSITY OF LEEDS

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International Journal papers:

1. **R. Moccia**, F. Ficuciello et al. ”Multiple Tasks Execution using Control Barrier Functions in Surgical Robotics”, *in submission (title is provisional)*, 2021.

2. **R. Moccia**, C. Iacono, B. Siciliano, F. Ficuciello, ”Vision-based Dynamic Virtual Fixtures for Tools Collision Avoidance in Robotic Surgery”, IEEE Robotics and Automation Letters, vol. 5, no. 2, pp. 1650-1655, June 2020.

3. H. Liu, M. Selvaggio, P. Ferrentino, **R. Moccia**, S. Pirozzi, U. Bracale, F.Ficuciello, ”The MUSHA Hand II: A Multi-Functional Hand for Robot-Assisted Laparoscopic Surgery”, IEEE/ASME Transactions on Mechatronics, vol. 26, no. 1, pp. 393-404, February 2020.

Products

International conference papers:

1. D.E. Canbay, P. Ferrentino, H. Liu, **R. Moccia**, S. Pirozzi, B. Siciliano, F. Ficuciello, ”Calibration of tactile/force sensors for grasping with the PRISMA Hand II”, Proc. IEEE/ASME International Conference on Advanced Intelligent Mechatronics, In proceedings, Deft, Netherlands, 2021.
2. **R. Moccia**, C. Iacono, B. Siciliano, F. Ficuciello, ”Vision-based Dynamic Virtual Fixtures for Tools Collision Avoidance in Robotic Surgery”, IEEE RAL Paper presented at IEEE International Conference on Robotics and Automation, Virtual Conference, 2020.
3. **R. Moccia**, M. Selvaggio, L. Villani, B. Siciliano, F. Ficuciello, ”Vision-based Virtual Fixtures Generation for Robotic-Assisted Polyp Dissection Procedures”, Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, Macau, China, November 2019, pp. 7928-7933.

Products

International conference papers:

4. M. Selvaggio, A. M. Ghalamzan E., **R. Moccia**, F. Ficuciello and B. Siciliano, ”Haptic-Guided Shared Control for Needle Grasping Optimization in Minimally Invasive Robotic Surgery”, Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, Macau, China, November 2019, pp. 7734-7939.
5. C. Iacono, **R. Moccia**, B. Siciliano, F. Ficuciello, ”Forbidden Region Virtual Fixtures for Surgical Tools Collision Avoidance”, Proc. Institute for Robotics and Intelligent Machine the Conference, Rome, Italy, October 18-20, 2020.

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Workshops papers:

7. 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.

8. M. Selvaggio, A. M. Ghalamzan E., **R. Moccia**, F. Ficuciello and B. Siciliano, ”Haptic-guided shared control for needle grasping optimization in minimally invasive robotic surgery”, Proc. Institute for Robotics and Intelligent Machine the Conference, Rome, Italy, October 18-20, 2019.

9. **R. Moccia**, M. Selvaggio, F. Ficuciello, ”Haptic-guided shared control for needle grasping optimization in minimally invasive robotic surgery”, Hamlyn Symposium Workshop: From BCI to human robot augmentation, London, England, June 23-26, 2019.

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Workshops papers:

1. M. Selvaggio, A. M. Ghalamzan E., **R. Moccia**, F. Ficuciello, B. Siciliano, ”Haptic-guided needle grasping in minimally invasive robotic surgery”, IEEE ICRA Workshop - Next Generation Surgery: Seamless Integration of Robotics, Machine Learning and Knowledge Representation within the Operating Rooms, Montreal, Canada, May 20-24, 2019.

10. **R. Moccia**, M. Selvaggio, B. Siciliano, A. Arezzo, F. Ficuciello, ”Vision-based virtual fixtures generation for MIRS dissection tasks”, 9th Joint Workshop on New Technologies for Computer/Robot Assisted Surgery, Genova, Italy, March 21-22, 2019.