Ph.D itee

INFORMATION TECHNOLOGY ELECTRICAL ENGINEERING

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Tutor: Bruno Siciliano

XXXI Cycle - III year presentation

Sensory-Motor Enhancement in Minimally Invasive Robotic Surgery

UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

Background & Info

- **M.Sc degree:** Automation and Control Engineering from University of Naples Federico II

- **Working team:** ICAROS center, PrismaLab, University of Naples Federico II

- **Collaborations:** University of Rome la Sapienza, Hamlyn center Imperial college of London

- **Supervisor:** Prof. Bruno Siciliano

- **Fellowship program:** "Borsa di Ateneo"

icaros prisma LAB SAPIENZA UNIVERSITÀ DI ROMA The Hamlyn Centre for Robotic Surgery

Experience Abroad

The Hamlyn Centre for Robotic Surgery

Topic: Development of assistive strategies for suturing in Minimally Invasive Robotic Surgery

Start: 1 October 2017

End: 31 March 2018

Prof. Guang-Zhong Yang
Director of the Hamlyn centre

Imperial college of London

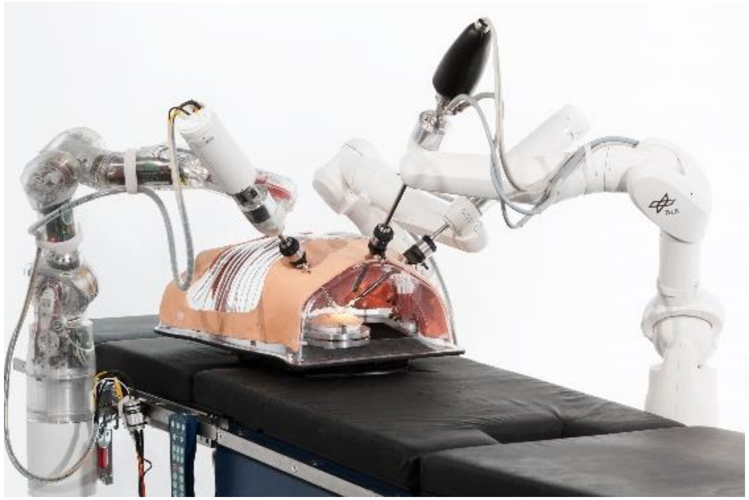
Credits

	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	**Summary**	**Total**	Check
Modules	20		6			8	7	**21**	10	3	3	2	0	0	5	**13**	0	0	0	0	0	0	0	**0**	**34**	30-70
Seminars	5	1,6	0		1	0	3,3	**5,9**	5	0	0.8	0.8	0	2	1.9	**5.5**	0	0	0	0	4	0	0	**4**	**15**	10-30
Research	35	8,4	4	10	9	2	2	**35**	45	7	6.2	7.2	10	8	3.1	**42**	60	10	10	10	6	10	8	**54**	**131**	80-140
	60	10	10	10	10	10	12	**62**	60	10	10	10	10	10	10	**60**	0	0	0	0	0	0	0	**0**	**180**	180

Background

In the last two decades **Robotic Surgery** has been introduced as a new approach in **Minimally Invasive Surgery** with the aim of overcoming the limits of **Laparoscopic Surgery**.

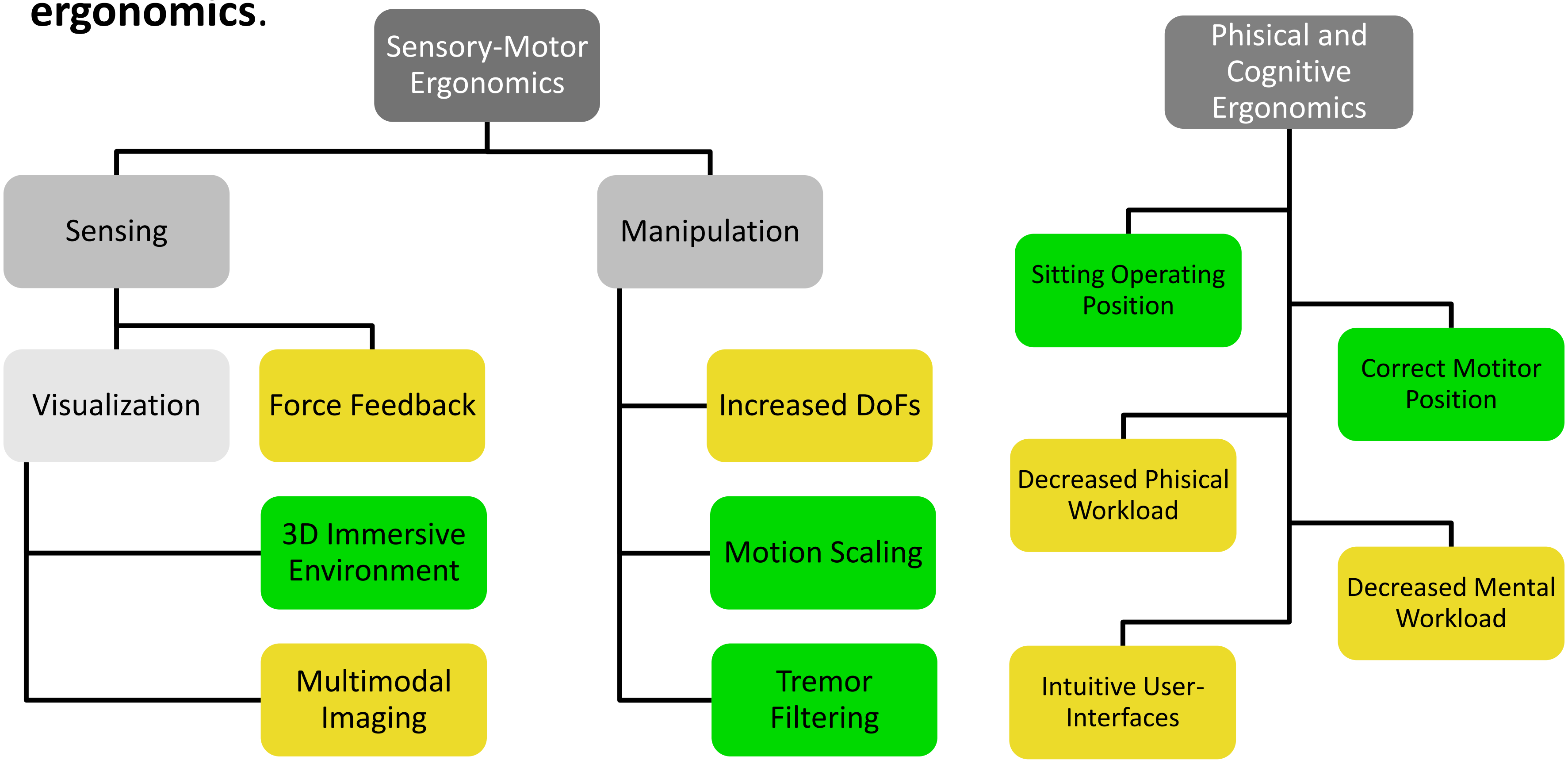




Background

A consequence of the advent of robotic surgery is an emerging **active partnership** between surgeons and machines whose analysis is subject of **ergonomics**.

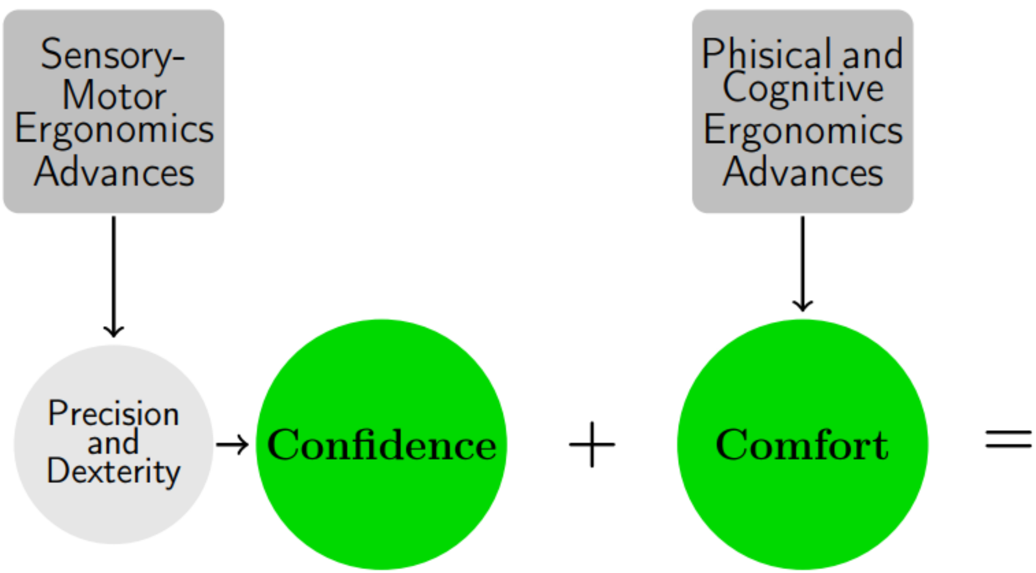


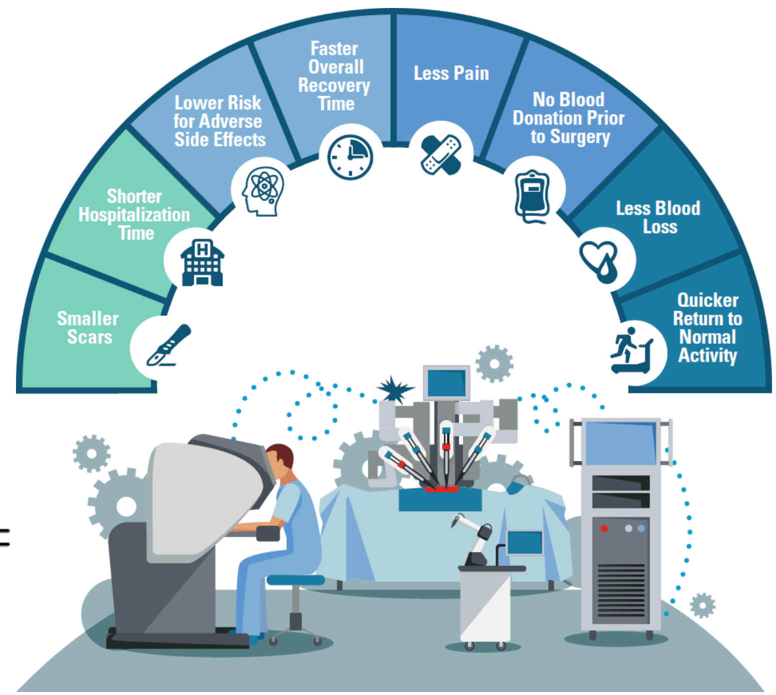
*N. Stylopoulos et al, SCNA 2003

Background

The **enhancement of surgeons sensory-motor capabilities** through advanced control paradigms and sensing/actuation devices is at forefront of research in robotic surgery.

This may leverage the development of next-generation surgical systems that enable **more precise and safer interventions even by less experienced surgeons.**



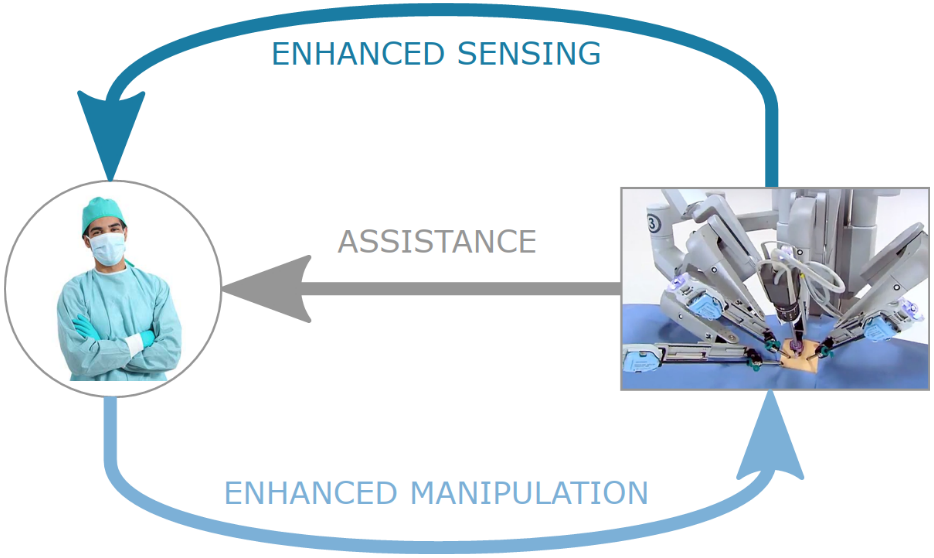


Motivations

Enhanced sensing: One of the major limitations of MIRS compared to classic laparoscopy is the lack of haptic force feedback. Surgeons can rely only on visual perception.

Enhanced actuation: Several tasks in MIRS could receive great benefit from the use of bio-inspired tools and advanced manipulation paradigms ensuring a dexterity level that cannot be guaranteed by currently available robotic and laparoscopic instruments.

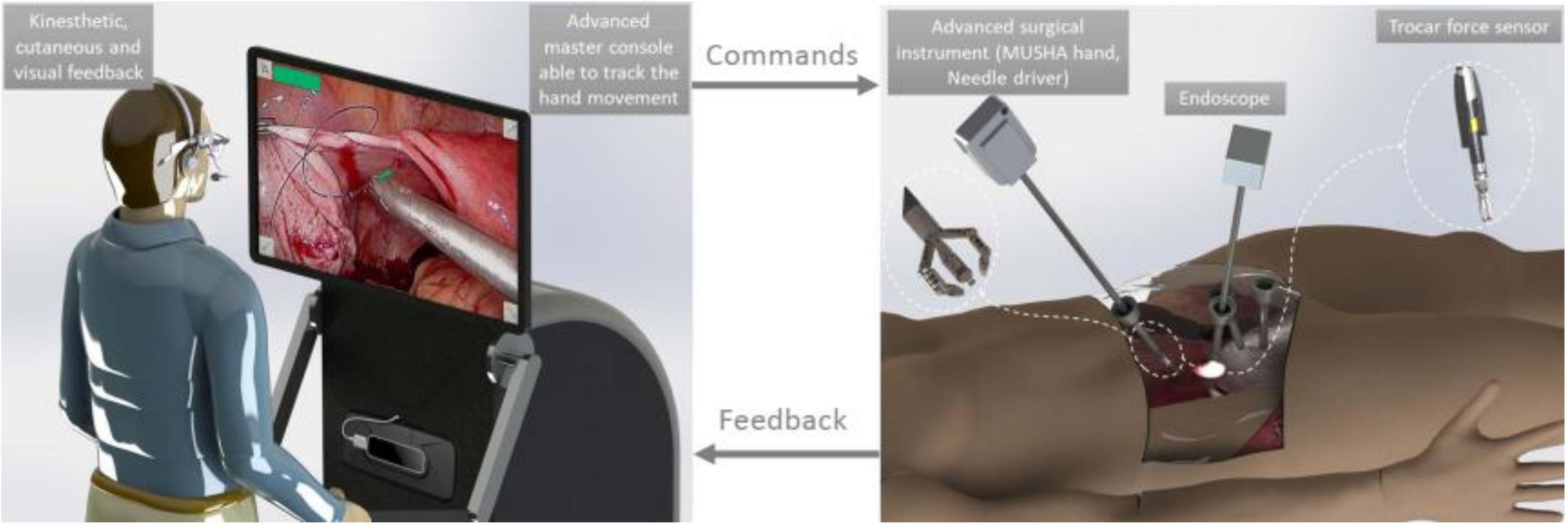
Assistance: The current paradigm of MIRS depends entirely on the individual surgeon's manual capability that in telemanipulation control the surgical instruments through the robot.



Our approach

Human-centred approach:

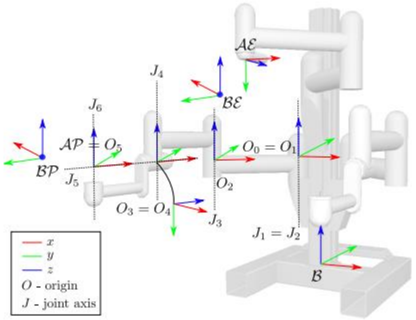
- Surgeons can perform the surgical procedure in a supervised, shared or fully telemanipulated way
- **Real-time dynamic active constraints** enhance the surgeon precision and reduce surgeon's mental/physical workload
- **Advanced sensing devices** and software embedded visual and force augmentation increase surgeon's perception capability improving safety and dependability
- **Highly dexterous anthropomorphic surgical instruments** increase surgeon's manipulation capability improving the applicability to different surgical procedures

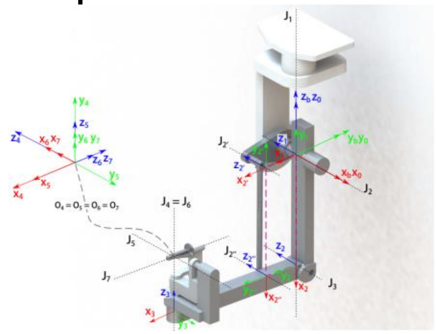


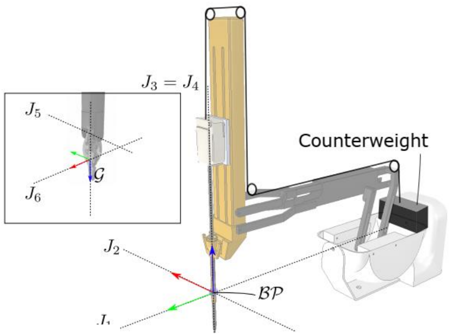
Modelling and simulation environment

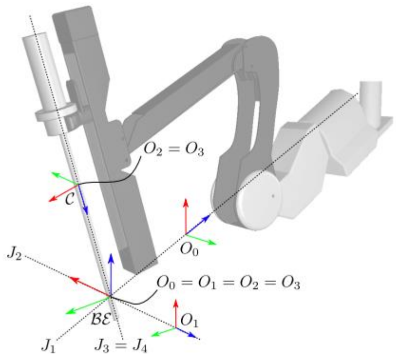
Kinematic modelling of the complete dVRK system and the identification of the dynamic parameters of its PSMs and MTMs arms.

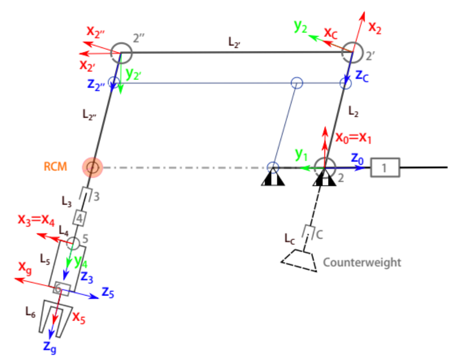
Using an **LMI-based approach** and a constrained optimization method we allow including the physical consistency constraints of the dynamic parameters in the identification procedure.









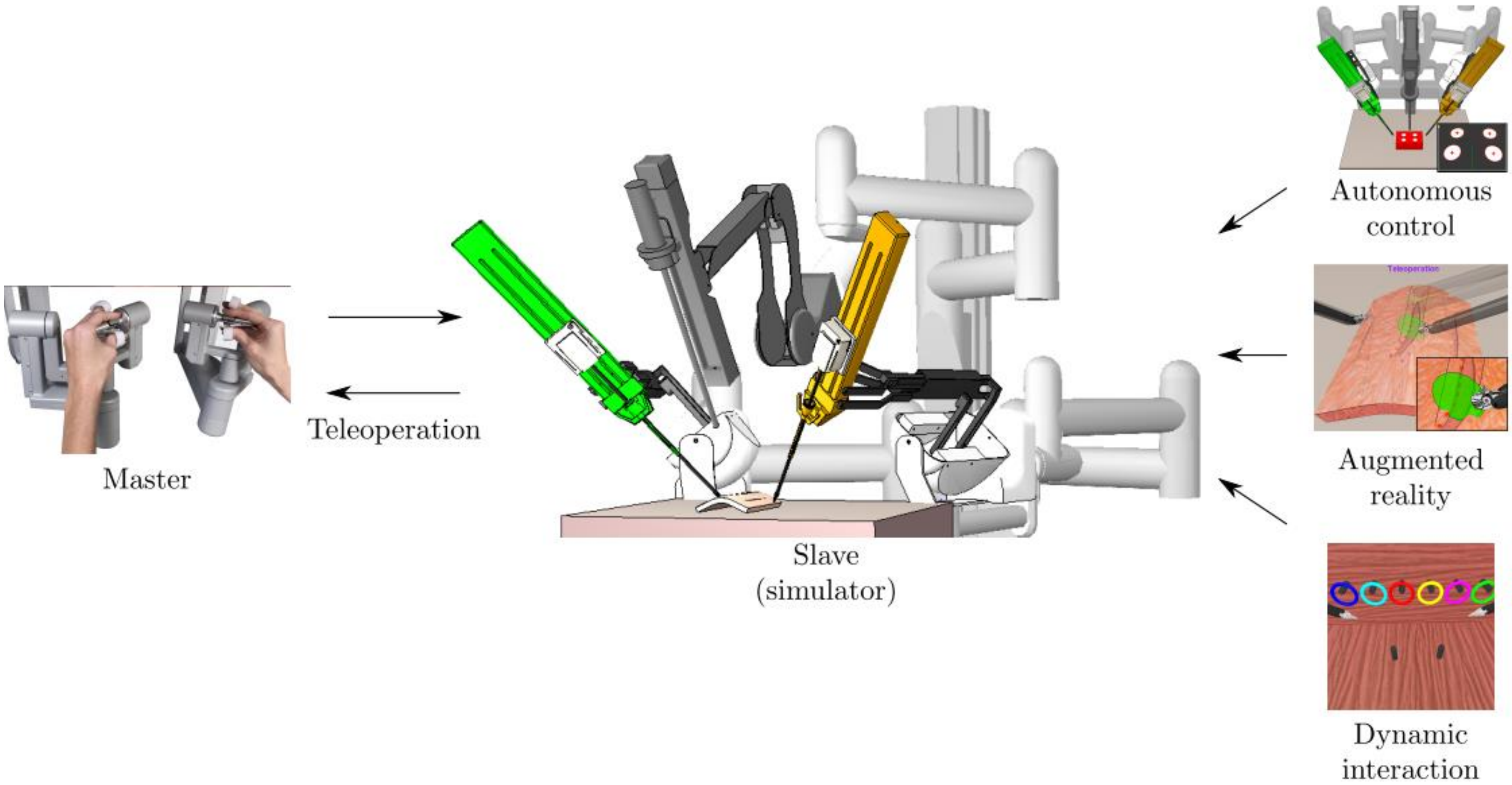


*G.A. Fontanelli et al, IROS2018

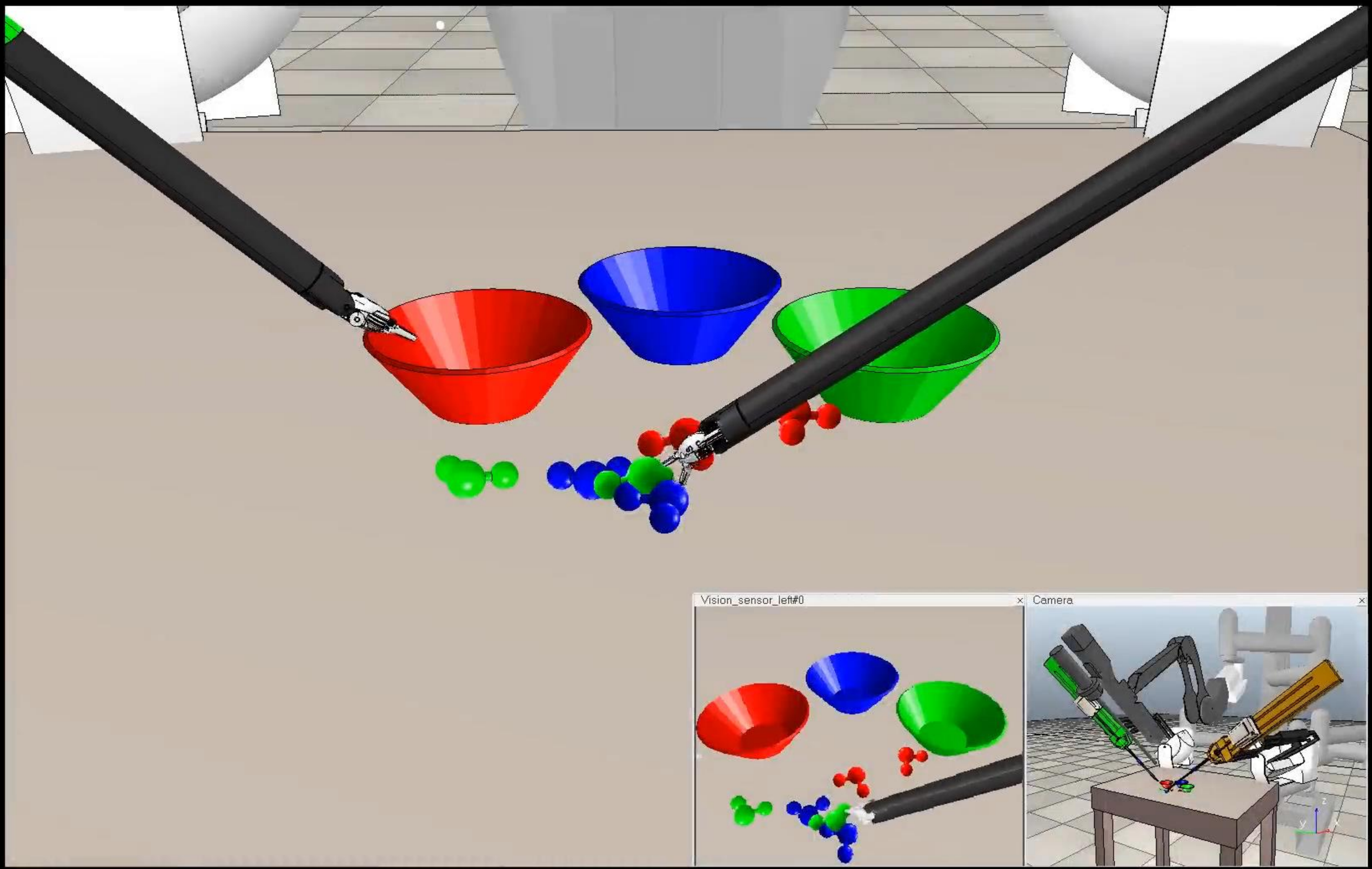
*G.A. Fontanelli et al, BioRob 2018

Modelling and simulation environment

A V-REP simulator for the da Vinci Research Kit robotic platform



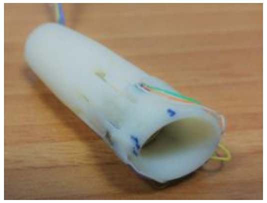
Modelling and simulation environment

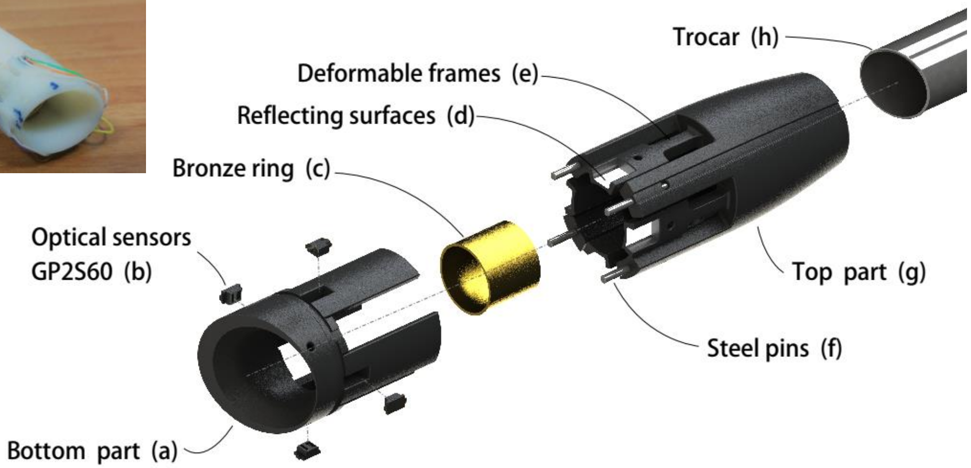


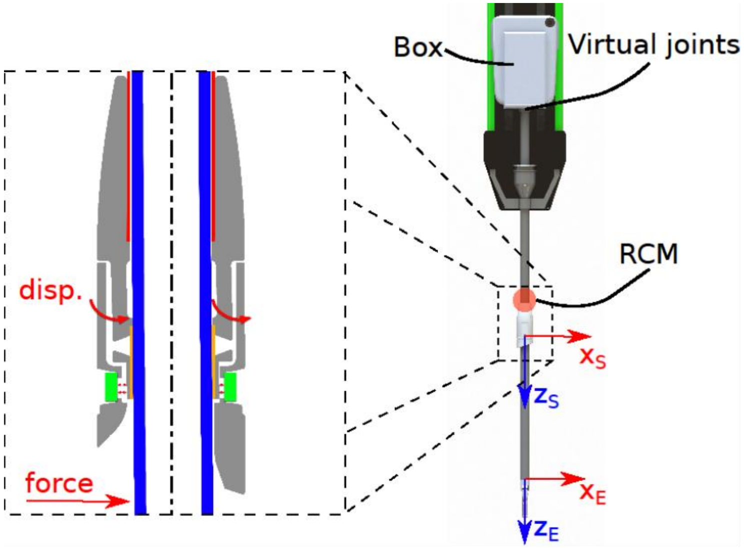
Sensing: force feedback

Estimation of the interaction forces on the surgical instrument, in the end-effector, measuring the forces exerted between the surgical instrument and the trocar

- cheap and disposable
- the force measurement is not influenced by the tendon-driven mechanism
- can be used with different laparoscopic instruments
- The instrument can be easily changed during the surgical procedure







*G.A. Fontanelli et al, IROS2017 + TMECH2018

Sensing: force feedback

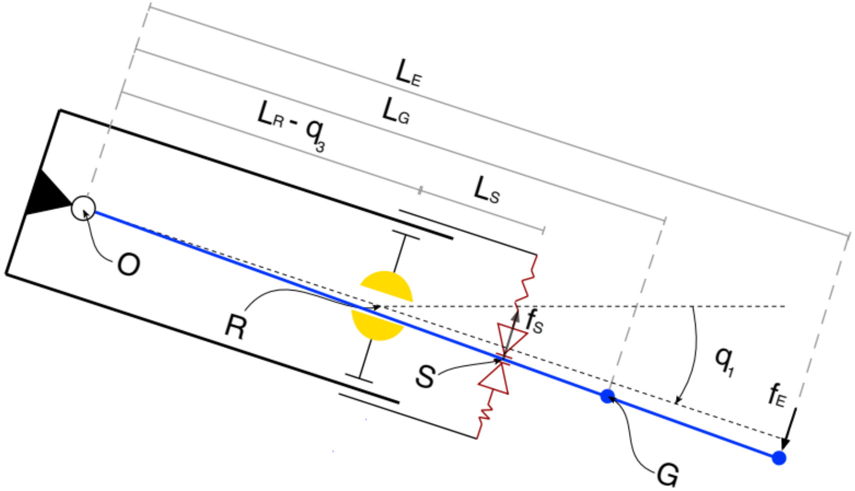
Derivation of the sensor dynamic model

$$\boldsymbol{r}_{45} = \boldsymbol{K}_{45I}\left(\boldsymbol{B}_{xy}(\boldsymbol{q})\dot{\boldsymbol{q}} - \int_0^t (\boldsymbol{r}_{45}(\sigma) + \boldsymbol{\tau}_S + \boldsymbol{n}_{xy}(\boldsymbol{q},\dot{\boldsymbol{q}}))\,,d\sigma\right)$$

$$\boldsymbol{f}_E = \begin{bmatrix} r_4/L_E \\ r_5/L_E \\ r_3 \end{bmatrix}$$

$$\boldsymbol{B}_{xy}(\boldsymbol{q}) = \begin{bmatrix} b_{x1} & 0 \\ 0 & b_{y2} \end{bmatrix}$$

$$\boldsymbol{n}_{xy}(\boldsymbol{q},\dot{\boldsymbol{q}}) = \begin{bmatrix} c_{x1}\dot{q}_1 + c_{x2}\dot{q}_2 + c_{x3}\dot{q}_3 - g_x \\ c_{y1}\dot{q}_1 + c_{y3}\dot{q}_3 - g_y \end{bmatrix},$$



$$r_3 = k_{3I}\left(\boldsymbol{b}_z^T(\boldsymbol{q})\dot{\boldsymbol{q}} - \int_0^t (r_3(\sigma) + \tau_{3R} + n_z(\boldsymbol{q},\dot{\boldsymbol{q}}))\,d\sigma\right)$$

$$\boldsymbol{b}_z^T(\boldsymbol{q}) = [b_{z1} \quad b_{z2} \quad b_{z3}]$$

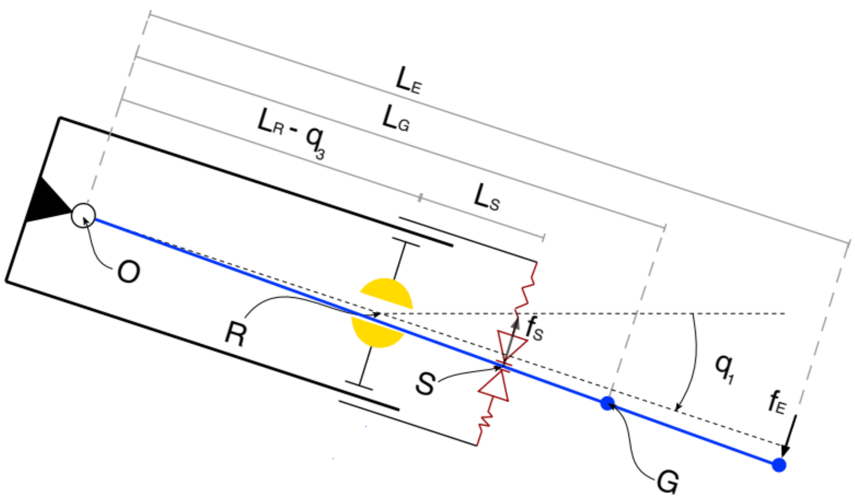
$$n_z(\boldsymbol{q},\dot{\boldsymbol{q}}) = c_{z1}\dot{q}_1 + c_{z2}\dot{q}_2 - g_z - f_z,$$

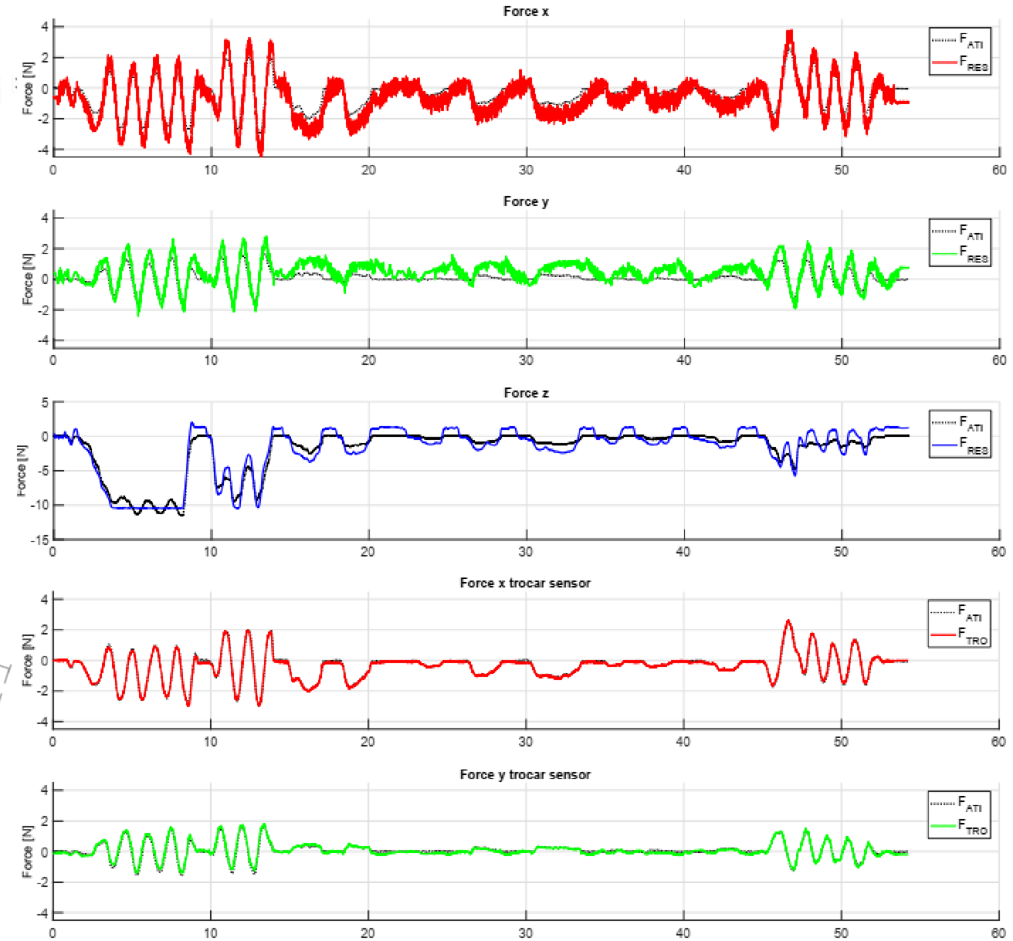
Sensing: force feedback

Derivation of the sensor dynamic model

r_{45}

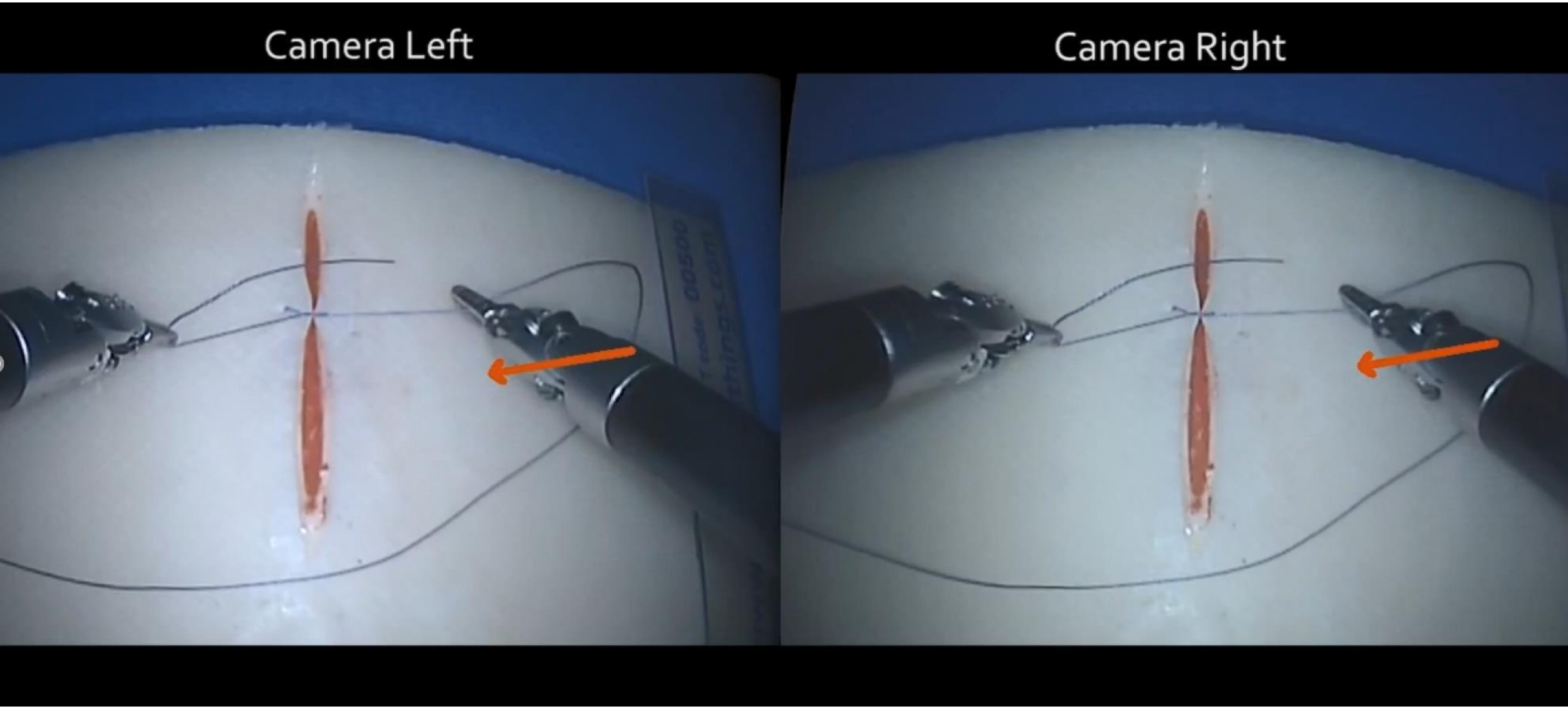
$$\boldsymbol{f}_E = \begin{bmatrix} r_4/L_E \\ r_5/L_E \\ r_3 \end{bmatrix}$$





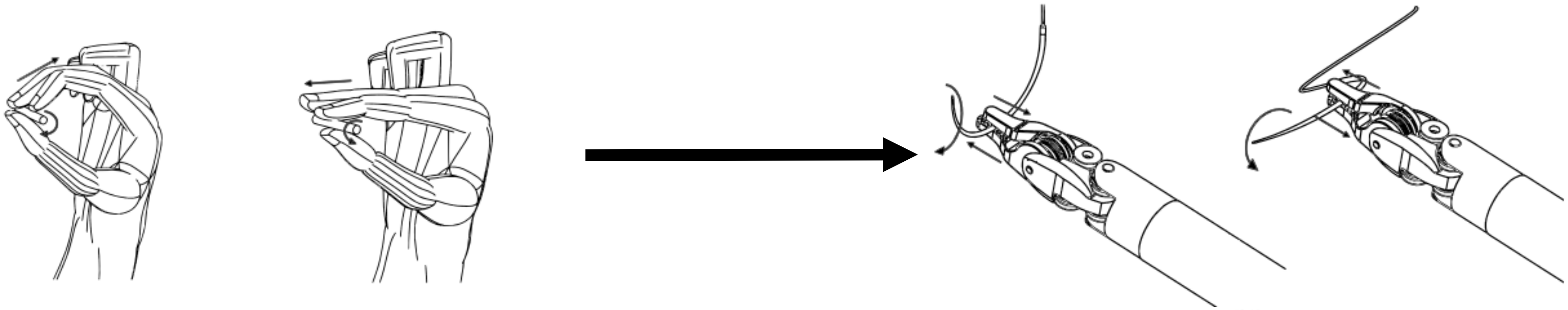
Sensing: force feedback

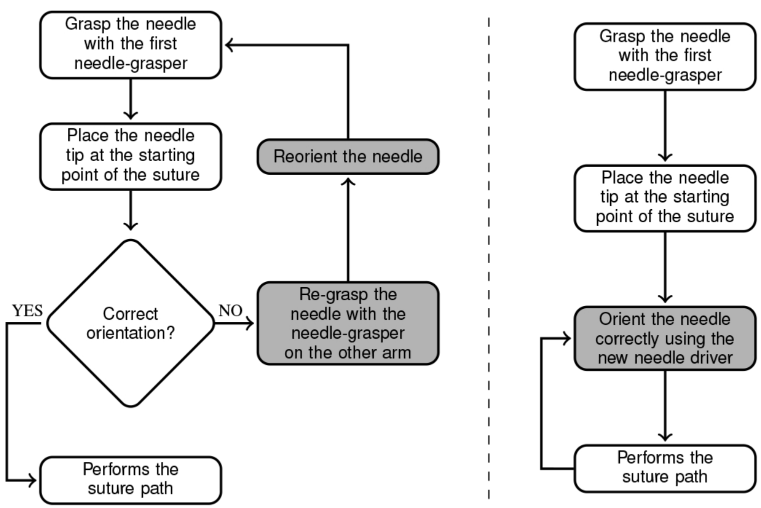
Force feedback through augmented reality

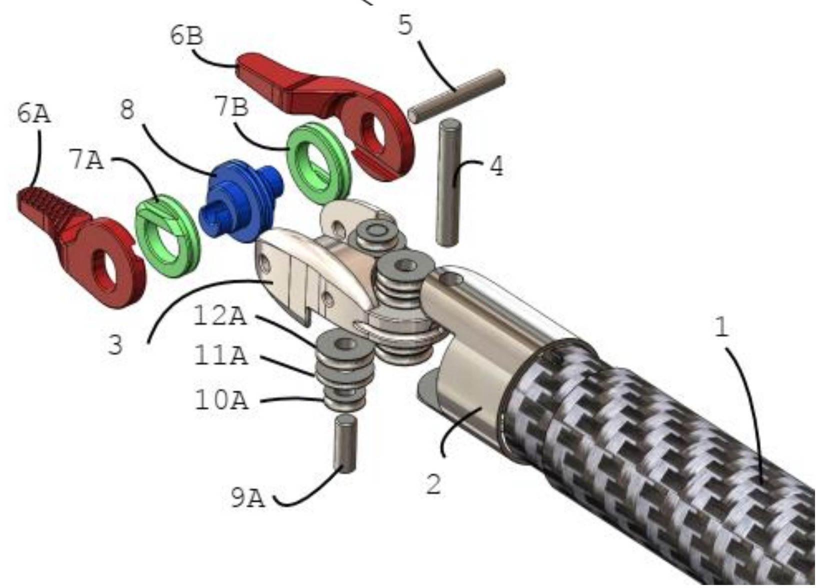


Actuation: suturing needle driver

A new laparoscopic needle driver with in-hand rolling capability for needle reorientation

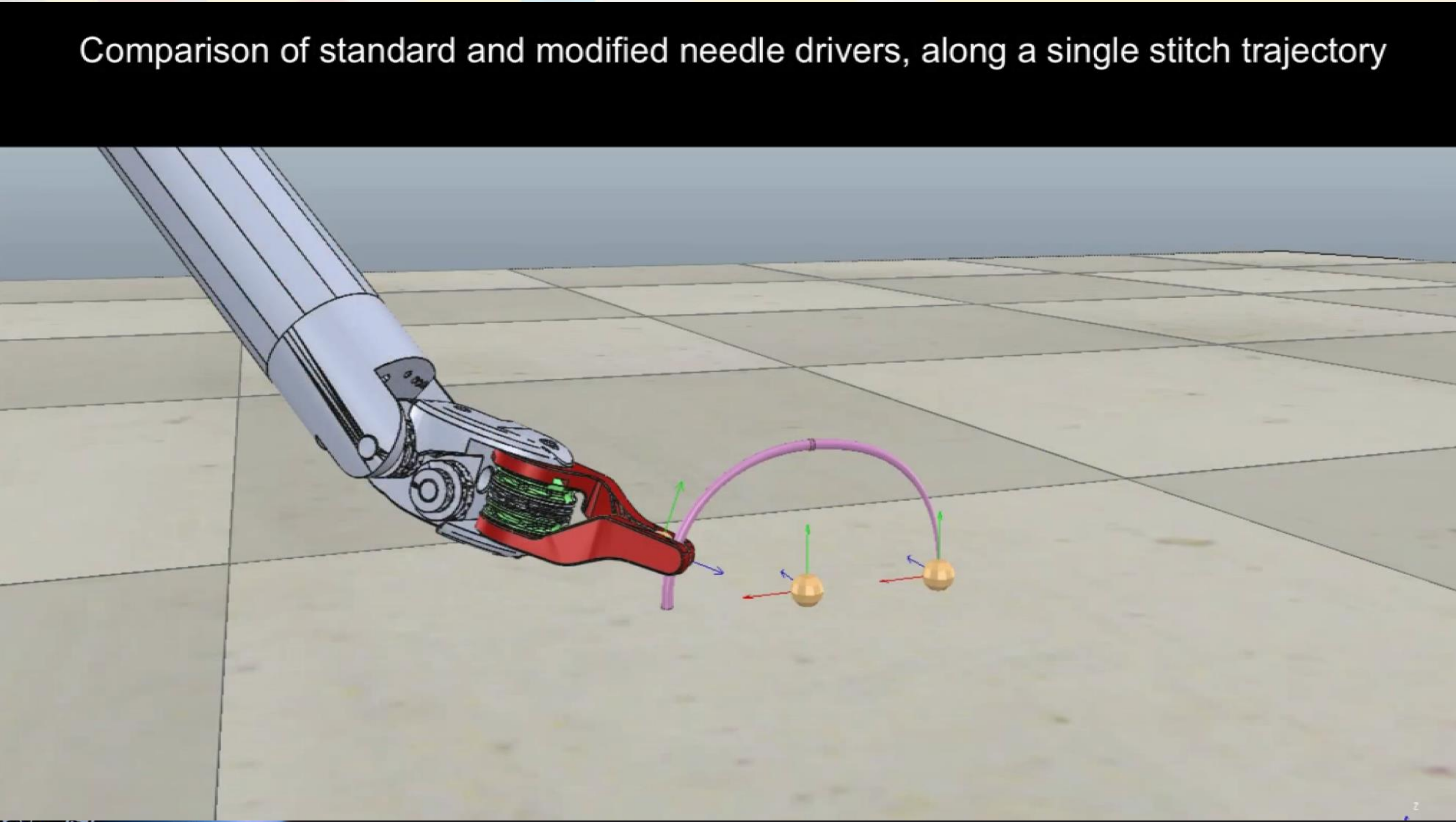






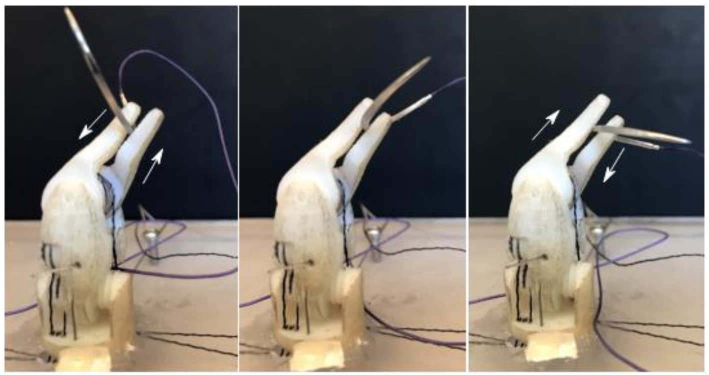
*G.A. Fontanelli et al, RAL2018 + ICRA2018 + HSMR2018

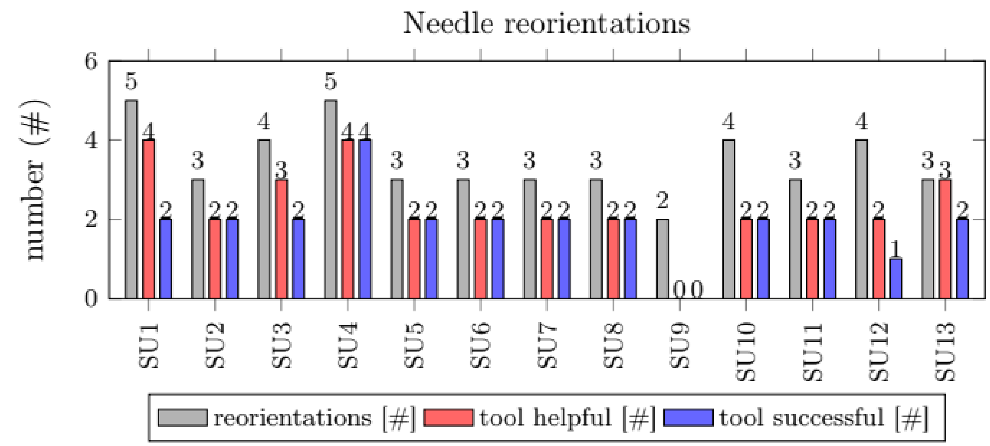
Actuation: suturing needle driver



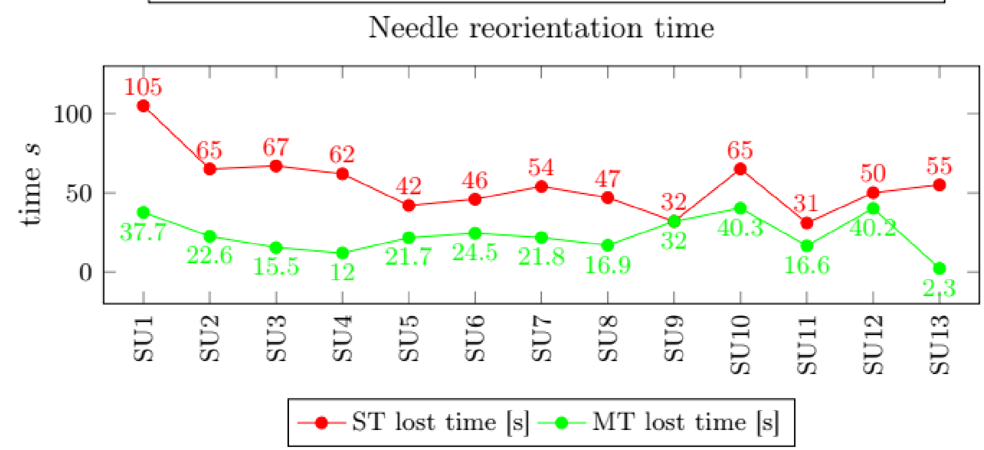
Actuation: suturing needle driver

The results show that our needle driver design allows a significant reduction of the time spent on needle reorientation





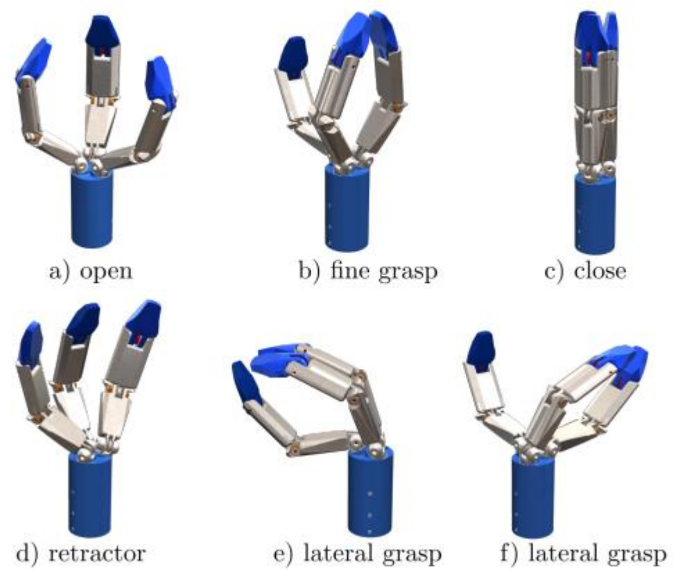
	R [mm]	$\beta = 0$	$\beta = \pi/12$	$\beta = \pi/4$
RB-1	0.25	$\pm$ 114°	$\pm$ 110.1°	$\pm$ 80.3°
SH-Plus	0.352	$\pm$ 88°	$\pm$ 85°	$\pm$ 62°
GL-222	0.38	$\pm$ 81°	$\pm$ 78.2°	$\pm$ 57°
UR-6	0.5	$\pm$ 57.5°	$\pm$ 55.3°	$\pm$ 40.5°

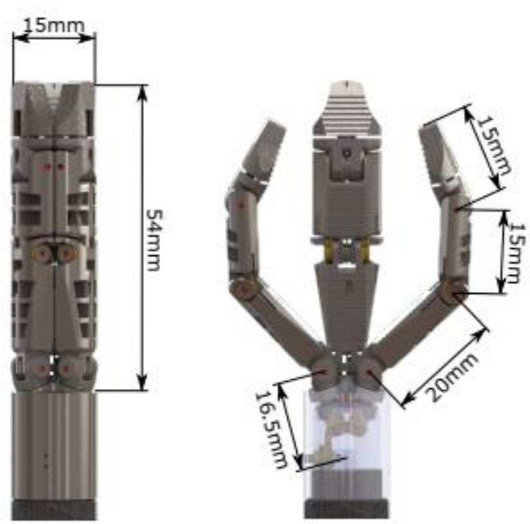


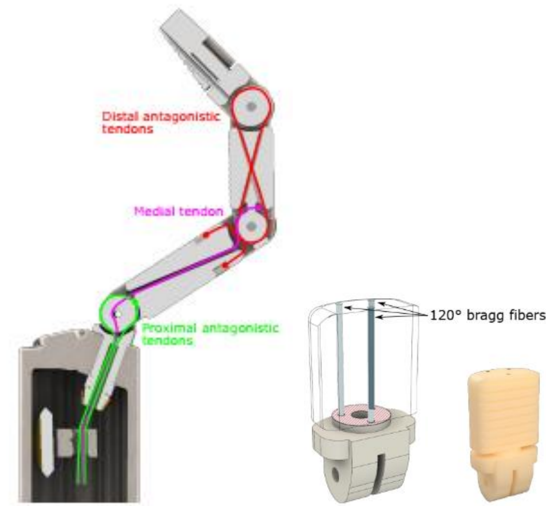
	stitches	reorient	help	success
#	65	45	30	25
		reorient/stitches	help/reorient	success/reorient
%		69%	66%	55%

Actuation: the MUSHA hand

- High DoFs to allow complex and human-like motions such as fine and power grasp
- Reconfigurable to allow tissue traction and manipulation and act as a retractor to gently manipulate organs such as the bowel.
- Underactuated to minimize the actuators number and reduce complexity
- Sensorized through FBG sensors to contribute to the diagnosis phase.



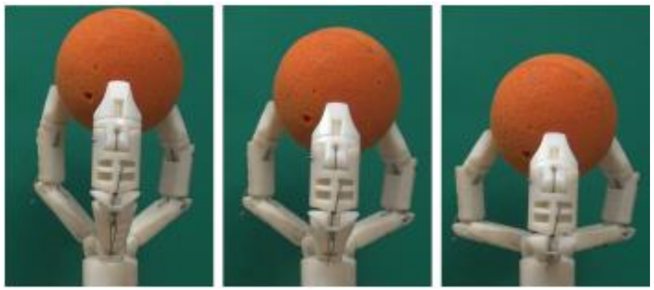


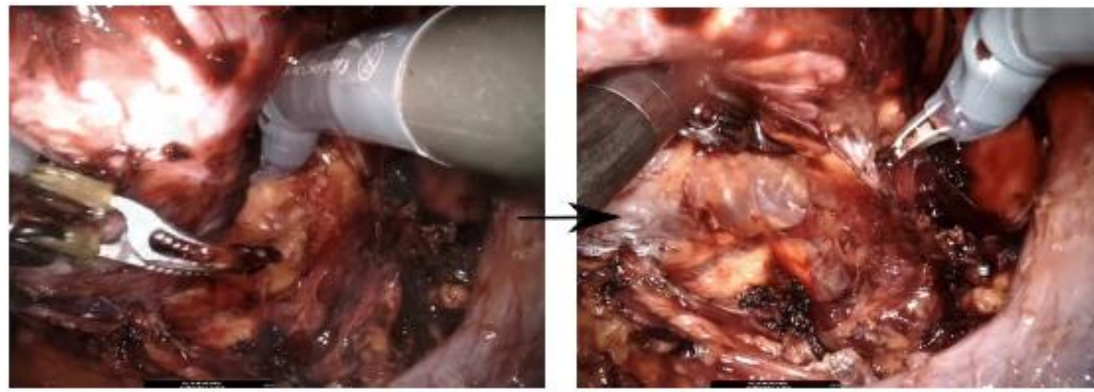


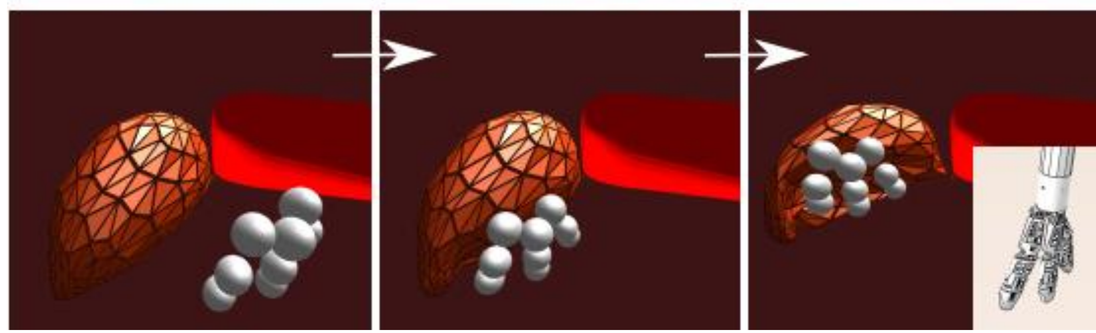
*M. Selvaggio, G.A. Fontanelli et al, JMRCAS 2018

Actuation: the MUSHA hand

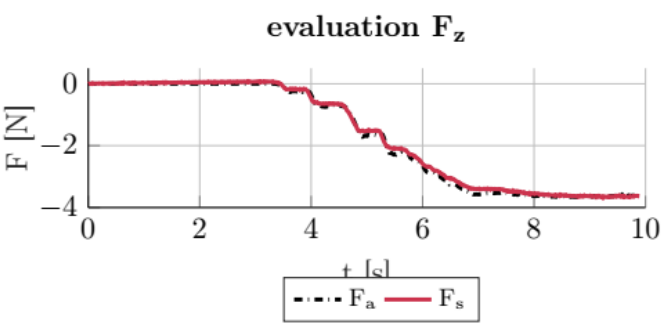
The effectiveness of the proposed design have been validated in simulation and using an in-scale 3D printed prototype.







Z-axis force estimated using the FBG finger tip force sensor

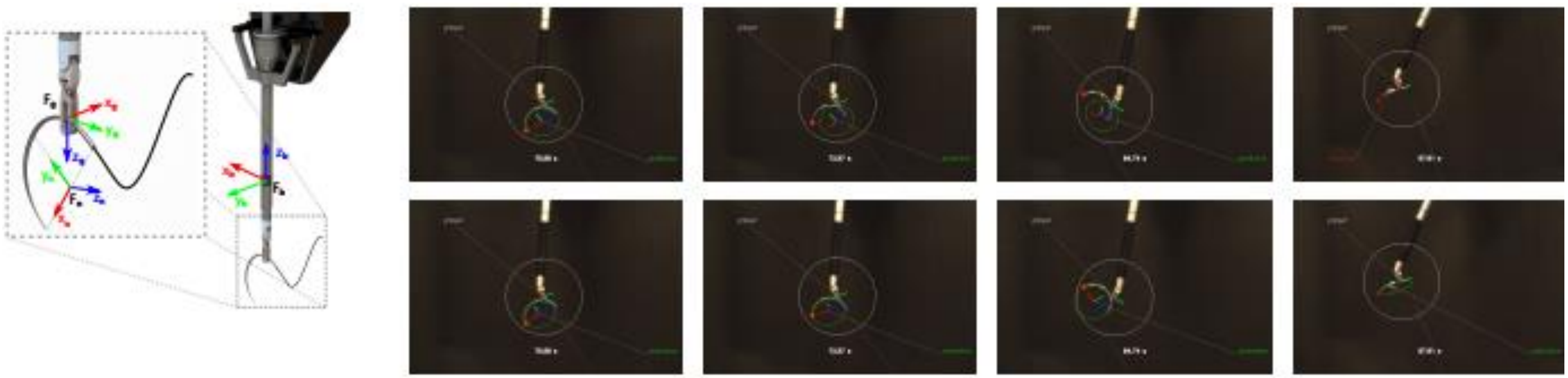


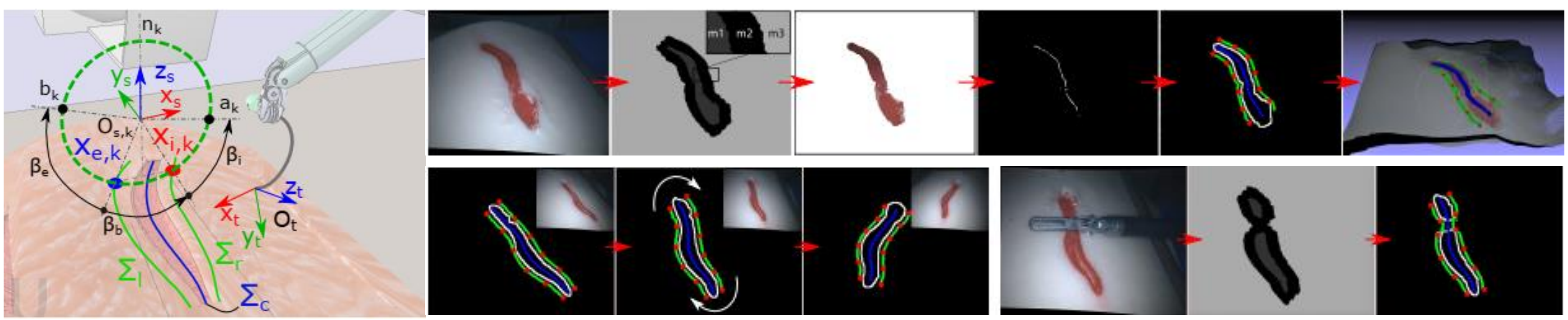
Assistance

*G.Z. Yang et al, Science Robotics 2017

Assistance: enhanced robot contextual knowledge of the environment

- Needle tracking using a non-linear Kalman filter
- Wound tracking using a GrabCut-based segmentation algorithm and a spline-based wound model

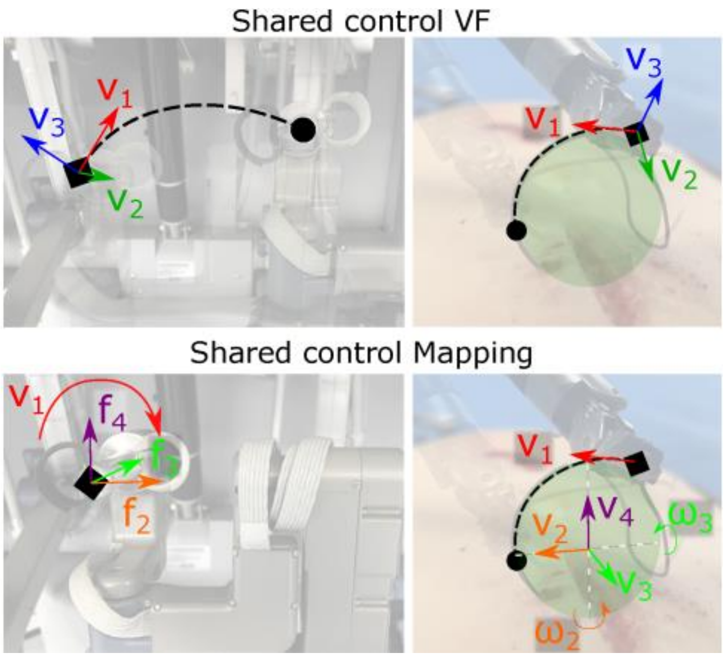




*M. Ferro, G.A. Fontanelli et al, CRAS2018 *G.A. Fontanelli et al, HSMR2018

Assistance: suturing

Comparison between different assistive control strategies



Supervised control

$$v_p(\sigma(t)) = \begin{bmatrix} R_s^p & -R_s^p S\left(R_p^s p_p - p_t^s\right) \\ 0 & R_s^p \end{bmatrix} v_t^s(\sigma(t))$$

Shared control using VFs

$$v_{md}(\bar{\sigma}_f) = \begin{bmatrix} \frac{1}{s} R_s^m & -\frac{1}{s} R_s^m S\left(R_p^s p_p - p_t^s\right) \\ 0 & R_s^m \end{bmatrix} v_t^s(\bar{\sigma}_f)$$

$$v_p(\bar{\sigma}_f) = \begin{bmatrix} s R_m^p & 0 \\ 0 & R_m^p \end{bmatrix} \begin{bmatrix} \dot{p}_m \\ \omega_{md}(\bar{\sigma}_f) \end{bmatrix}$$

$$\bar{\sigma} = \arg\min_{\sigma} \quad \| W_p(x_t^s(\sigma) - x_{te}^s) \|$$

Telemanipulation

$$v_p = \begin{bmatrix} s R_m^p & 0 \\ 0 & R_m^p \end{bmatrix} v_m$$

Shared control using a mapping

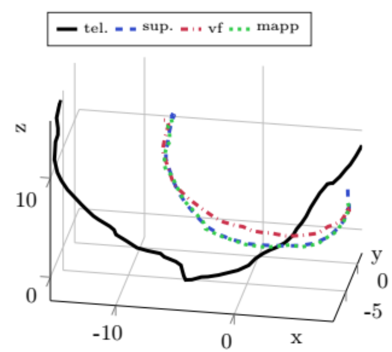
$$v_p(\sigma(t)) = \begin{bmatrix} R_s^p & -R_s^p S\left(R_p^s p_p - p_t^s\right) \\ 0 & R_s^p \end{bmatrix} v_t^s(\sigma(t))$$

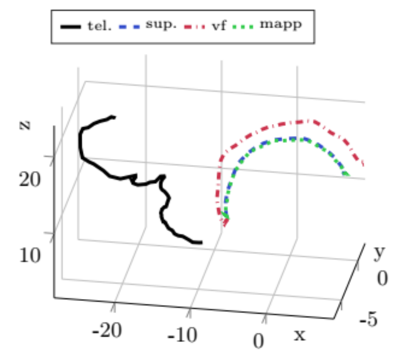
$$\dot{\sigma} = W_m (R_e^m)^T \omega_m$$

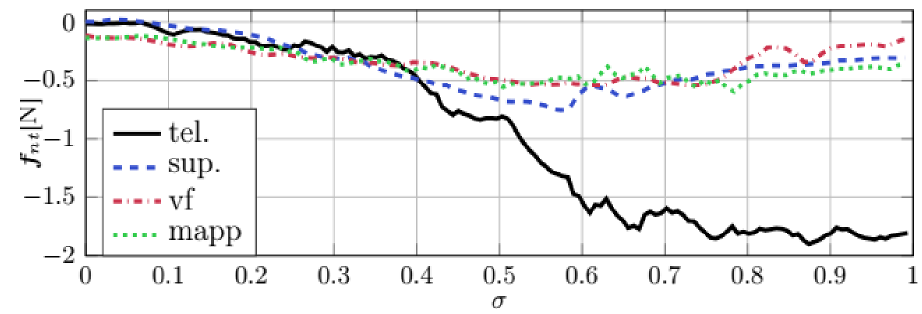
*G.A. Fontanelli et al, IROS2018

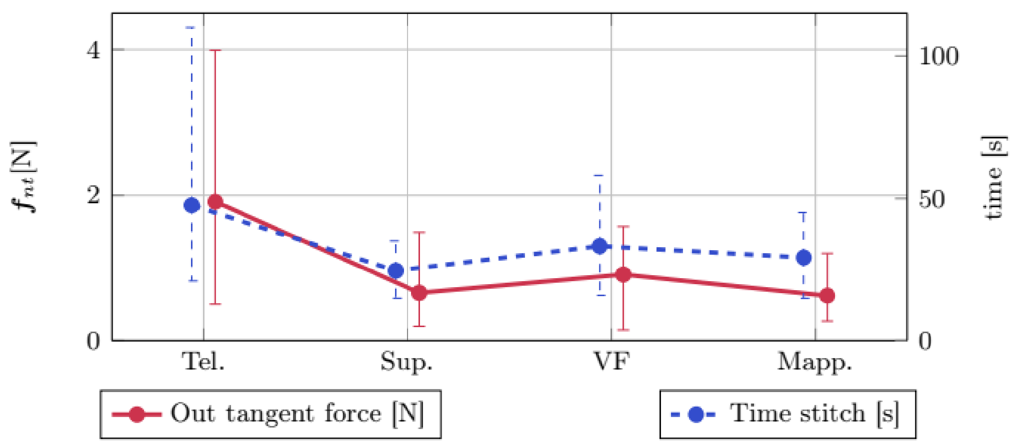
Assistance: suturing

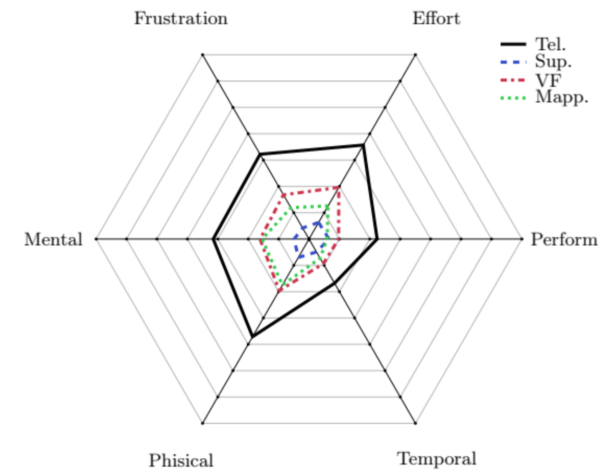
- The assistance reduce both time spent and needle-tissue force
- Solutions in which at least one degree of freedom, for the needle motion, is under the surgeon control are preferred by the surgeon











Assistance: dissection

Development of a passive Virtual Fixtures adaptation method

- Impedance controlled manipulator endowed with virtual fixtures control forces

$$\boldsymbol{M}\ddot{\tilde{\boldsymbol{x}}} + \hat{\boldsymbol{D}}\dot{\tilde{\boldsymbol{x}}} + \boldsymbol{K}_{\mathrm{vf}}\tilde{\boldsymbol{x}} = \boldsymbol{f}_{\mathrm{h}}, \qquad \boldsymbol{f}_{\mathrm{vf}}\left(\tilde{\boldsymbol{x}}, \dot{\tilde{\boldsymbol{x}}}\right) = -\boldsymbol{K}_{\mathrm{vf}}\tilde{\boldsymbol{x}} - \boldsymbol{D}_{\mathrm{vf}}\dot{\tilde{\boldsymbol{x}}},$$

- Passivity-based control

$$\begin{cases} \boldsymbol{M}\ddot{\tilde{\boldsymbol{x}}} + \hat{\boldsymbol{D}}\dot{\tilde{\boldsymbol{x}}} + \boldsymbol{K}_{\mathrm{vf}}\tilde{\boldsymbol{x}} = \boldsymbol{f}_{\mathrm{h}} \\ \dot{\boldsymbol{K}}_{\mathrm{vf}} = \alpha\left(\boldsymbol{\Lambda}_k\left(\boldsymbol{K}_{\mathrm{vf,d}} - \boldsymbol{K}_{\mathrm{vf}}\right) + \dot{\boldsymbol{K}}_{\mathrm{vf,d}}\right) \\ \dot{z} = \frac{\varphi}{z}\dot{\tilde{\boldsymbol{x}}}^{\mathrm{T}}\hat{\boldsymbol{D}}\dot{\tilde{\boldsymbol{x}}} - \frac{\gamma}{z}\frac{1}{2}\tilde{\boldsymbol{x}}^{\mathrm{T}}\dot{\boldsymbol{K}}_{\mathrm{vf}}\tilde{\boldsymbol{x}}, \end{cases}$$

$$\alpha = \begin{cases} 0 & \text{if } T \le \varepsilon \;\&\; \dot{\boldsymbol{K}}_{\mathrm{vf}} > 0 \\ 1 & \text{otherwise} \end{cases} \qquad \gamma = \begin{cases} \varphi & \text{if } \dot{\boldsymbol{K}}_{\mathrm{vf}} < 0 \\ 1 & \text{otherwise} \end{cases}$$

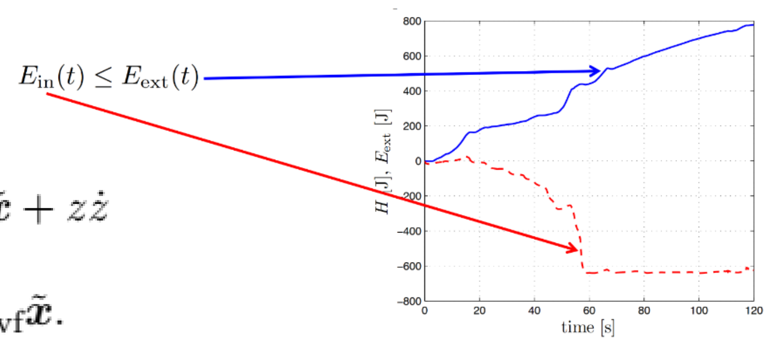
$$\varphi = \begin{cases} 1 & \text{if } T \le \bar{T} \\ 0 & \text{otherwise} \end{cases}$$

- Passivity analysis

$$\mathcal{H} = H + T = \frac{1}{2}\dot{\tilde{\boldsymbol{x}}}^{\mathrm{T}}\boldsymbol{M}\dot{\tilde{\boldsymbol{x}}} + \frac{1}{2}\tilde{\boldsymbol{x}}^{\mathrm{T}}\boldsymbol{K}_{\mathrm{vf}}\tilde{\boldsymbol{x}} + \frac{1}{2}z^2,$$

$$\dot{\mathcal{H}} = \dot{H} + \dot{T} = \dot{\tilde{\boldsymbol{x}}}^{\mathrm{T}}\boldsymbol{M}\ddot{\tilde{\boldsymbol{x}}} + \tilde{\boldsymbol{x}}^{\mathrm{T}}\boldsymbol{K}_{\mathrm{vf}}\dot{\tilde{\boldsymbol{x}}} + \frac{1}{2}\tilde{\boldsymbol{x}}^{\mathrm{T}}\dot{\boldsymbol{K}}_{\mathrm{vf}}\tilde{\boldsymbol{x}} + z\dot{z}$$

$$\dot{\mathcal{H}} = \dot{\tilde{\boldsymbol{x}}}^{\mathrm{T}}\boldsymbol{f}_{\mathrm{h}} - (1-\varphi)\,\dot{\tilde{\boldsymbol{x}}}^{\mathrm{T}}\hat{\boldsymbol{D}}\dot{\tilde{\boldsymbol{x}}} + (1-\gamma)\,\frac{1}{2}\tilde{\boldsymbol{x}}^{\mathrm{T}}\dot{\boldsymbol{K}}_{\mathrm{vf}}\tilde{\boldsymbol{x}}.$$



Assistance: dissection

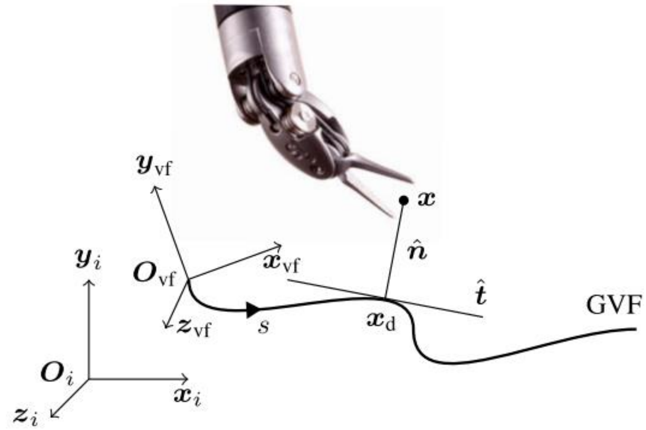
Development of a passive Virtual Fixtures adaptation method

- VF generation

$$\Gamma(s) = \arg\min_{\Gamma(s)} \left(\sum_i (y_i - \Gamma(s_i))^2 + \lambda \int (\Gamma''(s))^2 ds \right)$$

- VF adaptation

$$k_{\mathrm{vf,ii}}(\tilde{x}, t) = \beta(\tilde{x}, t) K_{\max} \quad \forall\, i = 1, \ldots, r$$



Pose adaptation

$$\beta(\tilde{x}) = \begin{cases} 0 & \text{if } |\tilde{x}| \geq l \\ \frac{1}{2}\left(1 + \cos\left(\frac{\pi(|\tilde{x}| - d)}{l - d}\right)\right) & \text{otherwise} \\ 1 & \text{if } |\tilde{x}| \leq d \end{cases}$$

Geometry adaptation

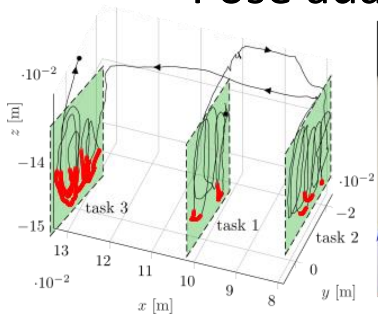
$$\beta(t) = \frac{1}{2}\left(1 + \cos\left(\frac{\pi(t - t_s)}{t_i - t_s}\right)\right) \quad t_s < t < t_i$$

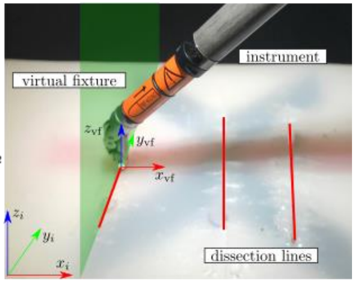
$$\beta(t) = \frac{1}{2}\left(1 - \cos\left(\frac{\pi(t - t_i)}{t_f - t_i}\right)\right) \quad t_i < t < t_f$$

*M. Selvaggio, G.A. Fontanelli et al, RAL2018 + IROS2018

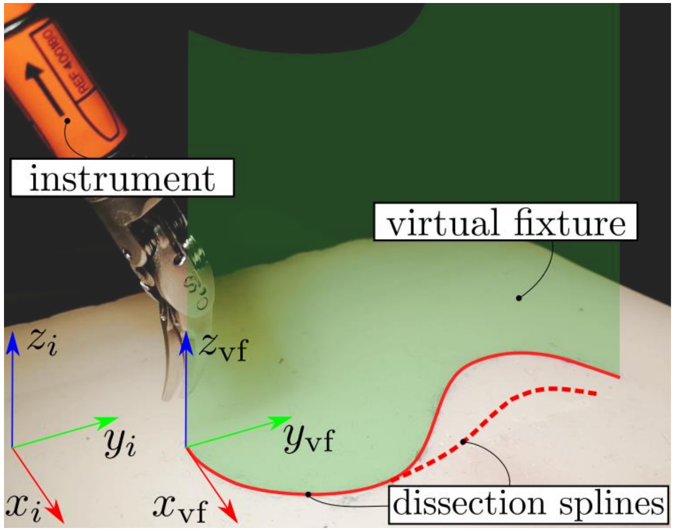
Assistance: dissection

Pose adaptation

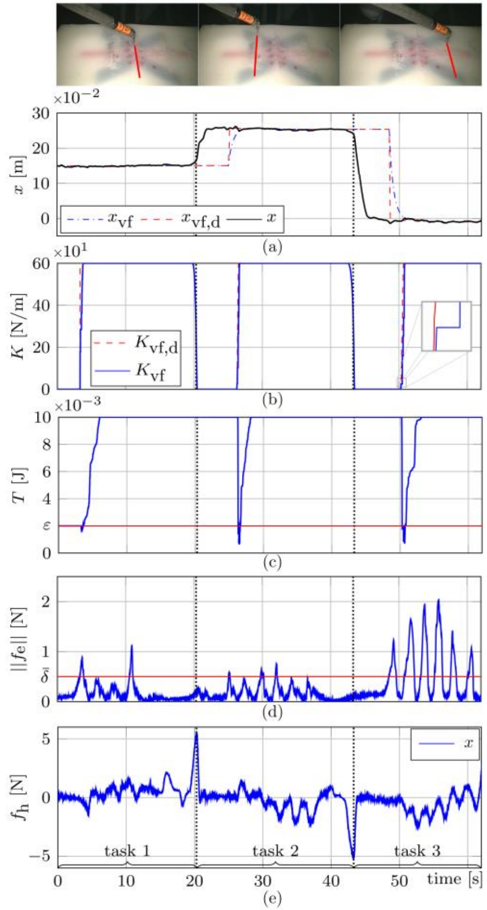




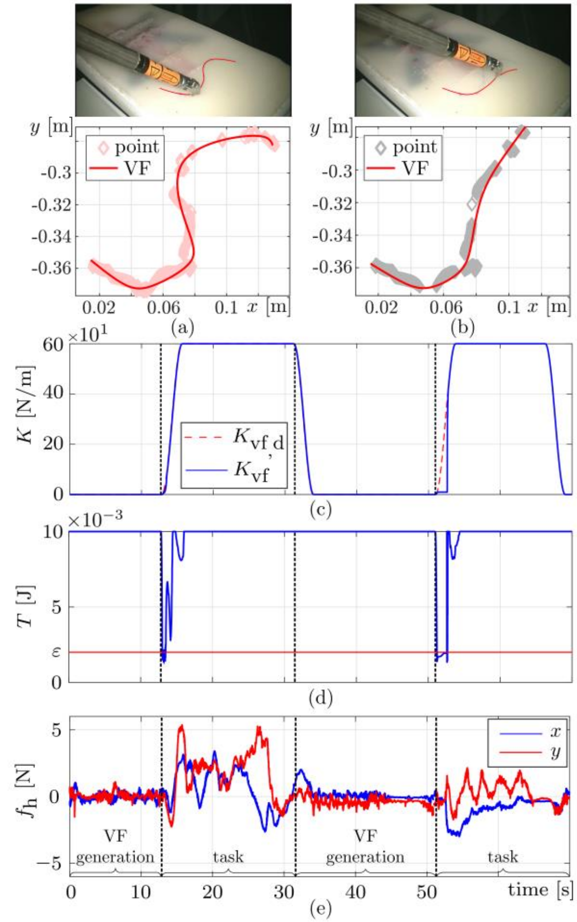
Geometry adaptation



Pose adaptation



Geometry adaptation



Products

International Journal paper published:

1. **G.A. Fontanelli**, M. Selvaggio, L.R. Buonocore, F. Ficuciello, L. Villani, B. Siciliano, "A New Laparoscopic Tool With In-Hand Rolling Capabilities for Needle Reorientation", Robotics and Automation Letters, July 2018, Presented at ICRA 2018
2. V. Lippiello, **G.A. Fontanelli**, F. Ruggiero "Image-Based Visual-Impedance Control of a Dual-Arm Aerial Manipulator", Robotics and Automation Letters, July 2018, Presented at ICRA 2018
3. M. Selvaggio, **G.A. Fontanelli**, F. Ficuciello, L. Villani, B. Siciliano, "Passive Virtual Fixtures Adaptation in Minimally Invasive Robotic Surgery", Robotics and Automation Letters, Oct 2018, Presented at IROS2018
4. Antoine Petit, Vincenzo Lippiello, **G.A. Fontanelli,** Bruno Siciliano, "Tracking elastic deformable objects with an RGB-D sensor for a pizza chef robot" in Robotics and automation systems, September 2016.
5. F. Ruggiero, A. Petit, D. Serra, A.C. Satici, J. Cacace, A. Donaire, F. Ficuciello, L.R. Buonocore, **G.A. Fontanelli**, V. Lippiello, L. Villani, B. Siciliano, "Nonprehensile manipulation of deformable objects: Achievements and perspectives from the RoDyMan project", Robotics and Automation Magazine, Sept 2018

International Journal paper under revision:

1. **G.A. Fontanelli**, L. R. Buonocore, F. Ficuciello, L. Villani, B. Siciliano, "An External Force Sensing System for Minimally Invasive Robotic Surgery", IEEE Transaction on Mechatronics, 2018, Under major revision
2. M. Selvaggio, **G.A. Fontanelli**, V.R Marrazzo, U. Bracale, A. Irace, G. Breglio, L. Villani, B. Siciliano, F. Ficuciello, "The musha underactuated hand for robot-aided minimally invasive surgery", International Journal of Medical Robotics and Computer Assisted Surgery, 2018, Under minor revision

Products

International Conference paper:

1. **G.A. Fontanelli**, G. Z. Yang, B. Siciliano, “A comparison of assistive methods for suturing in MIRS”, IROS 2018
2. **G.A. Fontanelli**, M. Selvaggio, M. Ferro, F. Ficuciello, M. Vendittelli, B. Siciliano, “A V-REP Simulator for the da Vinci Research Kit Robotic Platform”, BioRob 2018.
3. **G.A. Fontanelli**, F. Ficuciello, L. Villani, B. Siciliano, “Modelling and identification of the da Vinci Research Kit robotic arms”, IROS 2017
4. **G.A. Fontanelli**, L.R. Buonocore, F. Ficuciello, L. Villani, B. Siciliano, “A Novel Force Sensing Integrated into the Trocar for Minimally Invasive Robotic Surgery”, IROS 2017
5. F. Fazioli, F. Ficuciello, **G.A. Fontanelli**, B. Siciliano, L. Villani, “Implementation of a Soft-Rigid Collision Algorithm in an Open-Source Engine for Surgery Realistic Simulation, ROBIO 2016
6. R. Caccavale, M. Saveriano, **G.A. Fontanelli**, F. Ficuciello, D. Lee, A. Finzi, “Imitation Learning and Attentional Supervision of Dual-Arm Structured Tasks”, EPIGEN 2017
7. A. Petit, F. Ficuciello, **G.A. Fontanelli**, L. Villani, B. Siciliano, “Using Physical Modeling and RGB-D Registration for Contact Force Sensing on Deformable Objects”, ICINCO 2017

Workshops paper

1. **G.A. Fontanelli**, M. Selvaggio, F. Ficuciello, B. Siciliano, “The MUSHA hand: a New Three Fingered Underactuated Hand for Minimally Invasive Robotic Surgery”, SMITH 2017
2. **G.A. Fontanelli**, F. Ficuciello, L. Villani, B. Siciliano, “A Novel Force Sensor Integrated into the da Vinci Trocar for Minimally Invasive Robotic Surgery”, CRAS workshop 2017, finalist best paper award
3. **G.A. Fontanelli**, L. Zhang, G.Z. Yang, B. Siciliano, “Interactive Wound Segmentation and Automatic Stitch Planning”, HSMR2018
4. M. Selvaggio, **G.A. Fontanelli**, F. Ficuciello, L. Villani, B. Siciliano, “Enhancing Dexterity with a 7-DoF Laparoscopic Suturing Tool”, HSMR 2018
5. M. Selvaggio, **G.A.Fontanelli**, F.Ficuciello, L. Villani, B. Siciliano, “Task Classification of Robotic Surgical Reconstructive Procedures using Force Measurements”, CRAS workshop 2017
6. M. Ferro, **G.A.Fontanelli**, F. Ficuciello, B. Siciliano, M. Vendittelli, “Vision-based suturing needle tracking with Extended Kalman Filter”, CRAS workshop 2017
7. F. Fazioli, F. Ficuciello, **G.A. Fontanelli**, B. Siciliano, L. Villani, “Implementation of a Soft-Rigid Collision Algorithm in an Open-Source Engine for Surgery Realistic Simulation, CRAS 2016

Products

Patents:

1. New "*Laparoscopic tool with in hand rolling capabilities*" is **under second revision**.
2. New "*Laparoscopic instrument able to manipulate tissues and reconfigure itself as surgical retractor*" is **submitted**.
3. New "*Robotic arm tool for handling packages*" is **under submission**.

Awards:

1. **Switch 2 Product Innovation in Bioengineering Award (S2P GNB 2018),** *The MUSHA project*
2. **Best paper runner-up CRAS workshop 2017,** "*A Novel Force Sensor Integrated into the da Vinci Trocar for Minimally Invasive Robotic Surgery*
3. **Finalist we start challenge II ed,** *Hand Shake project*.
4. **Best project runner-up Hamlyn winter school 2016**

Committees:

1. **Organizer of the Workshop:** "*Learning and Autonomy for Medical Robotics*", Hamlyn Symposium on Medical Robotics, London, UK, June 24, 2018.

Thank you