INFORMATION TECHNOLOGY ELECTRICAL ENGINEERING Ph.D

Mario Selvaggio

Tutor: Bruno Siciliano

XXXII Cycle - III year presentation

Shared control telerobotic methods for industrial and surgical robotic systems

Università degli Studi di Napoli Federico II

Background and info

- **M. Sc. Degree**: Mechanical Engineering from University of Naples Federico II
- **Working team**: PRISMA Lab and ICAROS
- **Collaborations**:
  - IRISA, INRIA Rennes (France)
  - University of Rome La Sapienza (Italy)
  - University of Lincoln (UK)
  - University of California Santa Barbara (US)
- **Supervisor**: prof. Bruno Siciliano
- **Fellowship**: MIUR

Credits

	Credits year 1								Credits year 2								Credits year 3									
	Estimated	bimonth 1	bimonth 2	bimonth 3	bimonth 4	bimonth 5	bimonth 6	Summary	Estimated	bimonth 1	bimonth 2	bimonth 3	bimonth 4	bimonth 5	bimonth 6	Summary	Estimated	bimonth 1	bimonth 2	bimonth 3	bimonth 4	bimonth 5	bimonth 6	Summary	Total	Check
Modules	**20**	5	0	0	0	10	4	**19**	**10**	0	4	9	0	0	0	**13**	**0**	0	0	0	0	0	0	**0**	**32**	**30-70**
Seminars	**10**	0	0.8	8	1.9	0.4	0.4	**12**	**5**	0	2	0.2	0	0	2	**4.2**	**0**	0.3	0.4	0	0	0	0	**0.7**	**16**	**10-30**
Research	**30**	5	5	5	5	5	5	**30**	**45**	10	4	3	10	10	8	**45**	**60**	9	8	10	10	10	10	**57**	**132**	**80-140**
	60	10	5.8	13	6.9	15	9.4	**61**	**60**	10	10	12	10	10	10	**62**	**60**	9.3	8.4	10	10	10	10	**58**	**180**	**180**

Credits

Year	Lecture/Activity	Type	Credits	Certification	Notes
	MODULES				
1	Modelling, simulation and control of collective behaviour	Ad hoc module	2	x	
1	Introduction to artificial and computational intelligence	External Module	3	x	
1	Port-Hamiltonian modelling and passivity-based control of physical systems. Theory and applications	Doctoral School	4	x	
1	Analisi e controllo di reti e sistemi complessi	MS Module	6	x	
1	Machine Learning	Ad hoc module	4	x	
2	Geometric Theory of Soft Robots	Ad hoc module	4	x	
2	Delay differential equations and their applications	Ad hoc module	3	x	
2	Introduction to modeling and control of mechanical systems with constraints	Ad hoc module	2	x	
2	Control of Surgical Robots Summer School	Doctoral School	4	x	
	SEMINARS				
1	Icelandic centre of neurophysiology: aims, projects and opportunities for biomedical engineers student	Seminar	0.4	x	
1	Assessment, monitoring, prediction and decision making: different application from multimodal analysis	Seminar	0.4	x	
1	7th Joint Workshop on new Technologies for Computer/Robot Assisted Surgery	Conference	1.9	x	
1	Summer school on soft manipulation	External Seminar	8	x	summer s
1	From control to interaction in multi-robot systems	Seminar	0.4	x	
1	Dynamic control: mathematical challenges and applications	Seminar	0.4	x	
2	Approssimazione di problemi alle derivate parziali e applicazioni	Seminar	2	x	
2	How does mathworks accellerate the pace of engineering and science	Seminar	0.2	x	
2	A leap into funnctional data analysis: from theory to applications	Seminar	2	x	
3	The age of human-robot collabotation: deep sea exploration	Seminar	0.3	x	
3	Issues in robotic manipulation of deformable objects	Seminar	0.2	x	
3	Research work in active perception and robot interactive lab in IIT	Seminar	0.2	x	

Abroad periods

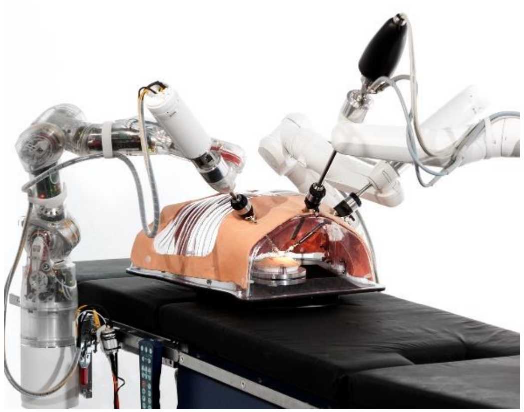
- **IRISA, INRIA Rennes** - Bretagne Atlantique Campus Universitaire de Beaulieu - Lagadic team, Rennes (France) - Nov. - Dec. 2017
- **IRISA, INRIA Rennes** - Bretagne Atlantique Campus Universitaire de Beaulieu - Rainbow team, Rennes (France) - Oct. - Dec. 2018
- **University of California Santa Barbara** - department of Mechanical Engineering - Hawkes group, Santa Barbara, California (US)

  June - Dec. 2019

Background

Telerobotics represents one of the earliest robotic application

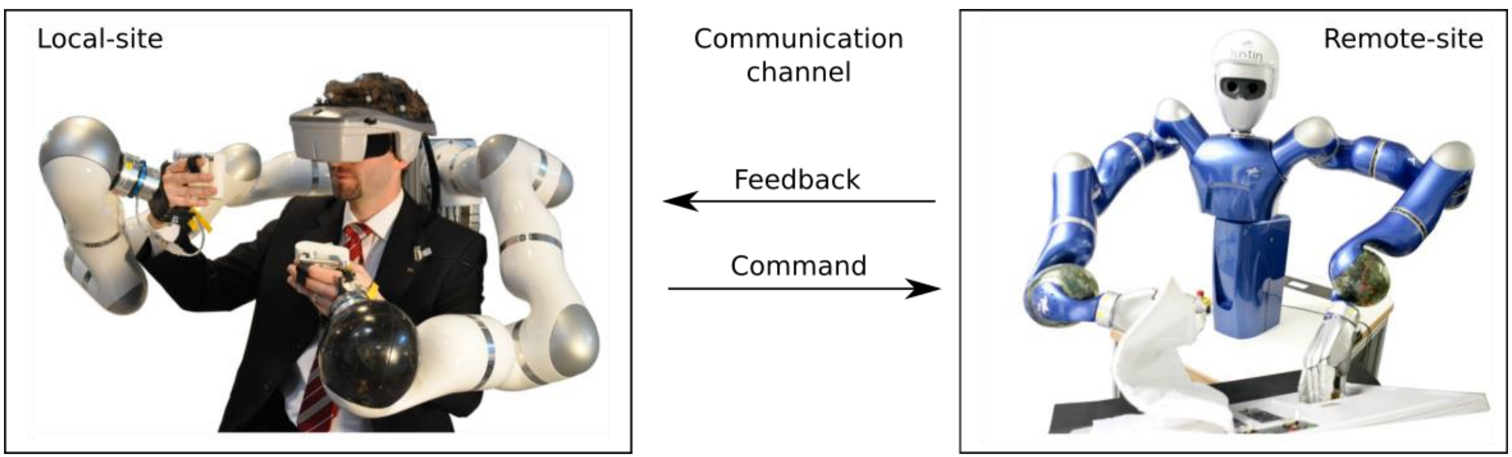
It allows operating in *hazardous* (e.g. nuclear industry), *dangerous* (e.g. disaster) or *different scale* (e.g. surgical) environments



Background

A telerobotic system is composed by a **master interface**, a **slave robot**, and a **communication channel**

To accomplish **difficult** tasks, the user needs to operate **complex** (e.g. many degrees of freedom) remote robots



Background

Shared-control telerobotic systems are those in which a human operator trades the control of the robotic system with an autonomous controller to achieve a common goal

Haptic guidance methods play a relevant role in telerobotic applications (e.g. to inform the operator about the system status/constraints)

Haptic-based shared control = Haptic guidance + shared control

Goal, motivation and approach

The **goal** of this work is to develop natural, efficient and safe haptic shared-control telerobotic architectures for the operator to accomplish tasks in non-trivial environments

The main **motivation** is the need of lowering down the physical and cognitive effort of the operator in control of the telerobotic system

Sensor-based autonomous control approaches are used to design haptic guidance for the operator, while **passivity-based control** guarantees a safe behavior of the telerobotic system

Shared control architectures for industrial applications

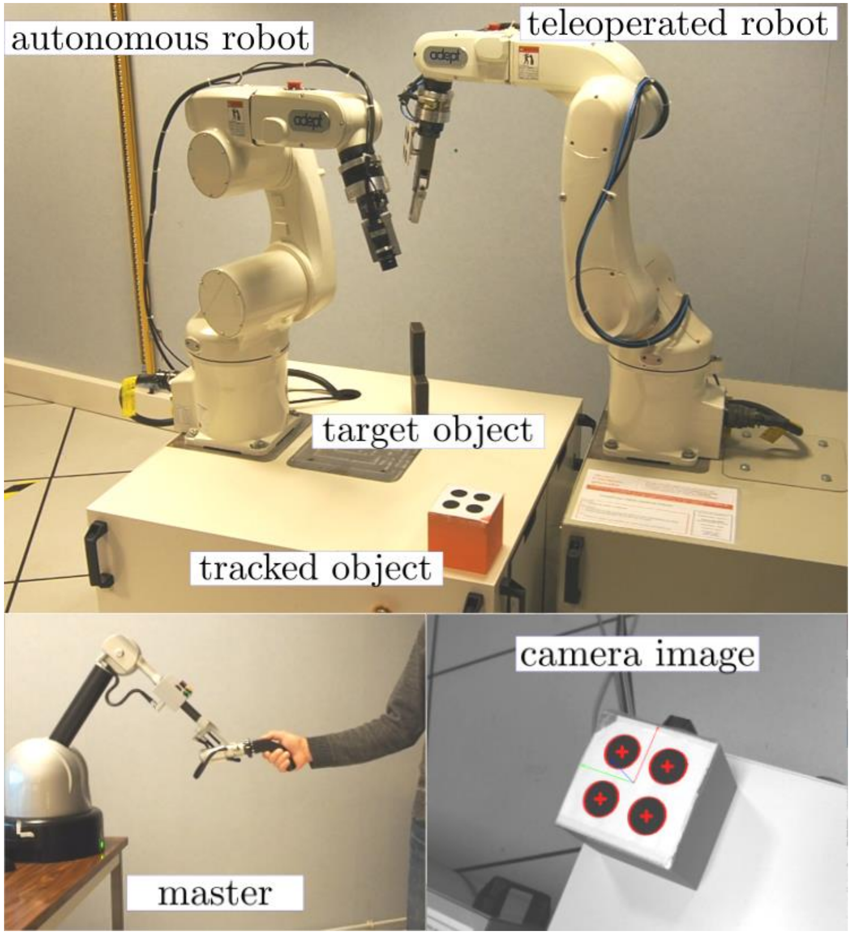
Collaboration with Inria INVENTEURS DU MONDE NUMÉRIQUE

Shared control for a dual-arm system

Problem: reduce the operator's workload during sort and segregation of nuclear waste

Solution: semi-autonomous vision-based and collision avoidance architecture

Results: human-subject study

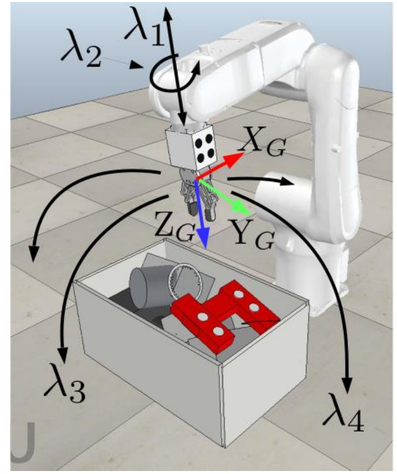


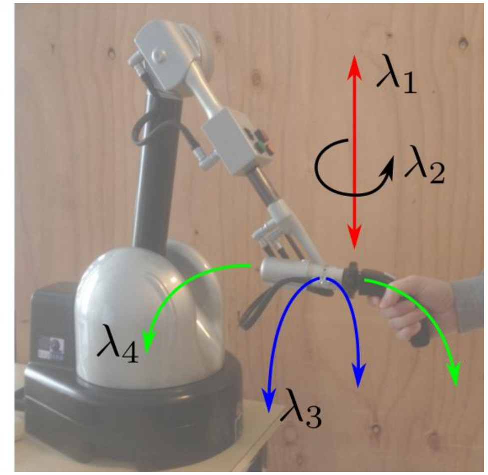
M. Selvaggio et al. "Haptic-based shared-control methods for a dual-arm system", RAL 2018

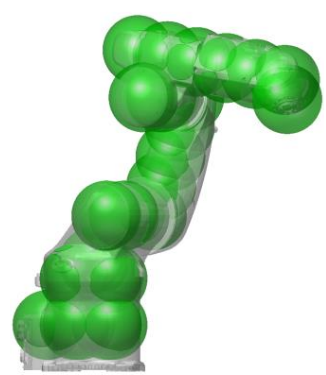
Shared control for a dual-arm system

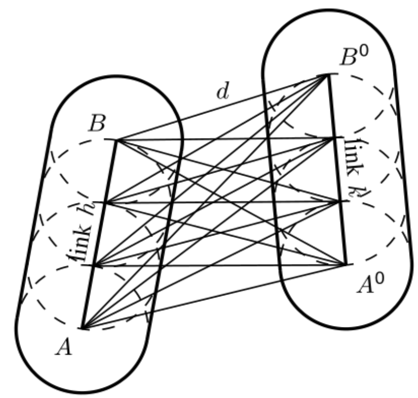
Features

- Vision-based semi-autonomous control
- Collision avoidance by reactive control
- Haptic guidance to inform about constraints
- Passivity analysis through port-Hamiltonian modeling









M. Selvaggio et al. “Haptic-based shared-control methods for a dual-arm system”, RAL 2018

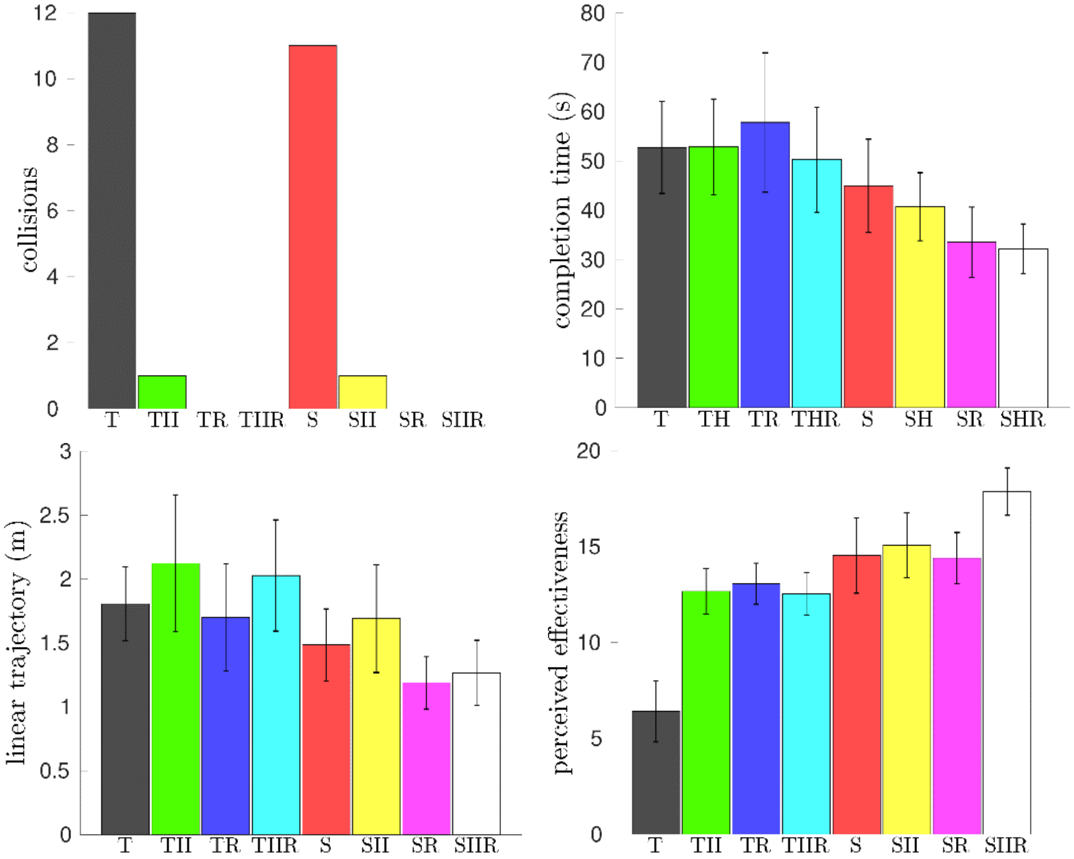
Shared control for a dual-arm system

Results

Anova

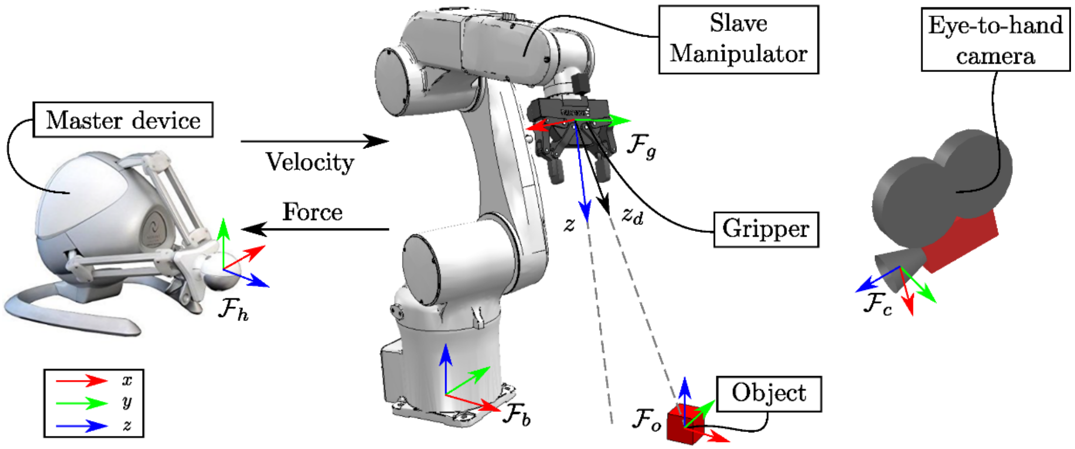
- Factors
- Human involvement (T vs. S)
- Haptic guidance (H vs. no H)
- Reactive behavior (R vs. no R)

- Metrics
- Collisions
- Completion time
- Linear Trajector
- Perceived effectiveness



M. Selvaggio et al. “Haptic-based shared-control methods for a dual-arm system”, RAL 2018

Task-prioritized shared control



Problem: reduce the operator's workload during sort and segregation of nuclear waste

Solution: passive task-prioritized shared control architecture

Results: 2-DoF control for a grasping task

M. Selvaggio et al. "Passive Task-Prioritized Shared-Control Teleoperation with Haptic Guidance", ICRA 2019

Task-prioritized shared control

Features

- Task-prioritized architecture

$$\dot{\boldsymbol{q}}_s = \dot{\boldsymbol{q}}_{s,a} + \dot{\boldsymbol{q}}_{s,u}, \qquad \dot{\boldsymbol{q}}_{s,a} = \sum_{i=1}^{r} \boldsymbol{\Lambda}_i \boldsymbol{P}_{i-1} \boldsymbol{J}_{s,i}^{\dagger} \tilde{\boldsymbol{\sigma}}_i$$

- Haptic guidance to inform about constraints

$$\dot{\boldsymbol{q}}_{s,u} = \boldsymbol{C} \dot{\boldsymbol{q}}_m$$

$$\boldsymbol{\tau}_m = -\boldsymbol{C}^{\mathrm{T}} \nabla \mathcal{H} \left(\boldsymbol{q}_s \right)$$

M. Selvaggio et al. "Passive Task-Prioritized Shared-Control Teleoperation with Haptic Guidance", ICRA 2019

Task-prioritized shared control

Features

- Passivity analysis

$$\mathcal{V}(\boldsymbol{q}_m, \boldsymbol{q}_s) = \frac{1}{2}\dot{\boldsymbol{q}}_m^{\mathrm{T}} \boldsymbol{M}_m \dot{\boldsymbol{q}}_m + \mathcal{H}(\boldsymbol{q}_s) + \frac{1}{2}\sum_{i=1}^{r} \tilde{\boldsymbol{\sigma}}_i^{\mathrm{T}} \tilde{\boldsymbol{\sigma}}_i$$

$$\dot{\mathcal{V}} = -\underbrace{\dot{\boldsymbol{q}}_m^{\mathrm{T}} \boldsymbol{B}_m \dot{\boldsymbol{q}}_m}_{\geq 0} + \underbrace{\dot{\boldsymbol{q}}_m^{\mathrm{T}} \boldsymbol{\tau}_h}_{\boldsymbol{y}^{\mathrm{T}}\boldsymbol{u}} + \underbrace{\left(\sum_{i=1}^{r} \boldsymbol{\Lambda}_i \boldsymbol{P}_{i-1} \boldsymbol{J}_{s,i}^{\dagger} \tilde{\boldsymbol{\sigma}}_i\right)^{\mathrm{T}} \nabla\mathcal{H}}_{=w} +$$

$$\underbrace{-\sum_{k=1}^{r} \tilde{\boldsymbol{\sigma}}_k \boldsymbol{J}_{s,k} \left(\sum_{i=1}^{r} \boldsymbol{\Lambda}_i \boldsymbol{P}_{i-1} \boldsymbol{J}_{s,i}^{\dagger} \tilde{\boldsymbol{\sigma}}_i\right)}_{\geq 0}$$

- Energy tanks passivity-based control

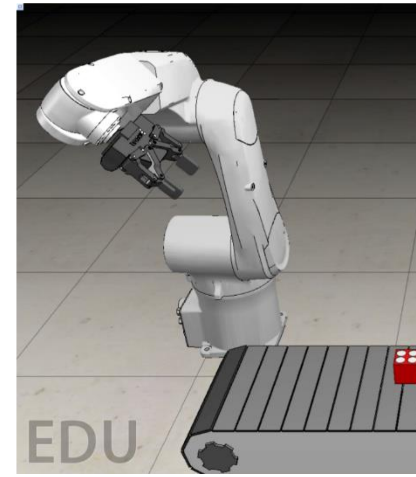
$$\mathcal{T}(z) = \frac{1}{2} z^2, \qquad \dot{z} = \frac{\varphi}{z} \dot{\boldsymbol{q}}_m^{\mathrm{T}} \boldsymbol{B}_m \dot{\boldsymbol{q}}_m - \frac{1}{z} \sum_{i=1}^{r} \gamma_i w_i \qquad \dot{\boldsymbol{q}}_{s,a}^{\alpha} = \sum_{i=1}^{r} \alpha_i \boldsymbol{\Lambda}_i \boldsymbol{P}_{i-1} \boldsymbol{J}_{s,i}^{\dagger} \tilde{\boldsymbol{\sigma}}_i$$

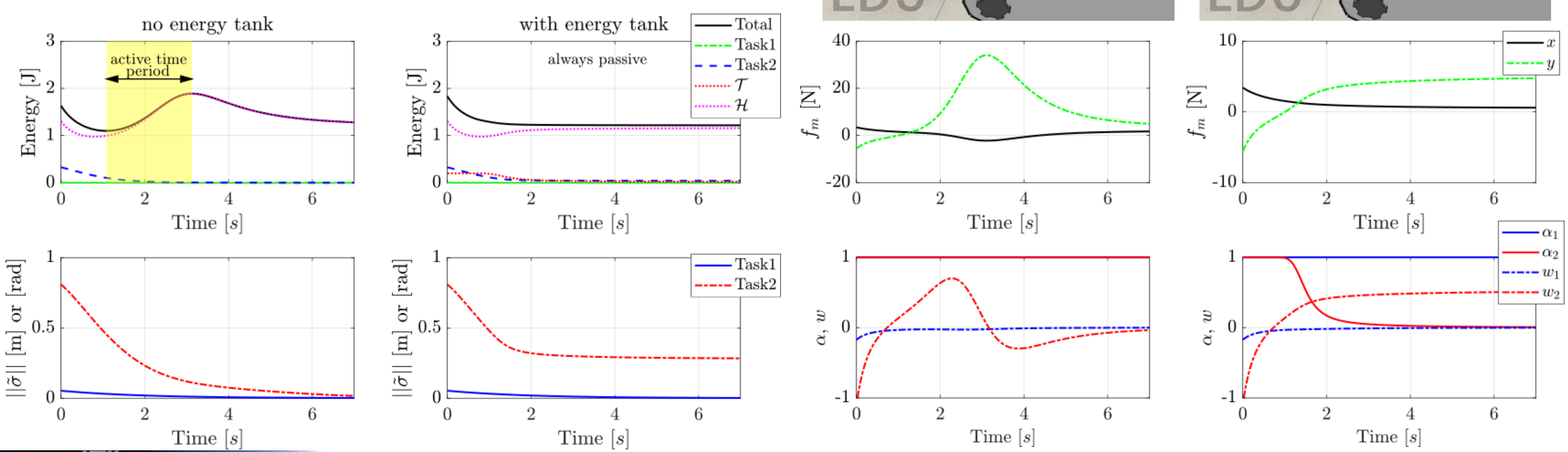
M. Selvaggio et al. “Passive Task-Prioritized Shared-Control Teleoperation with Haptic Guidance”, ICRA 2019

Task-prioritized shared control

Results

- The user can accomplish a grasping task using only 2-DoF
- Passivity (safety) is preserved during the teleoperated task

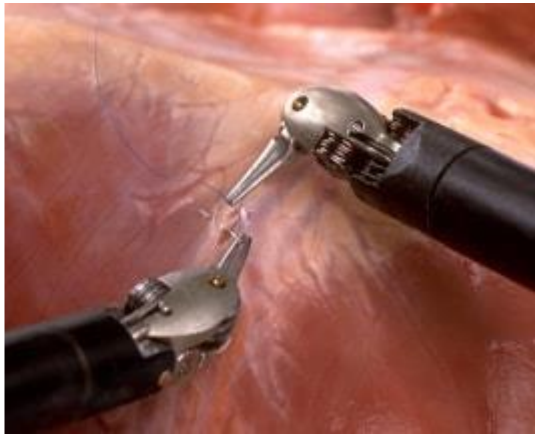


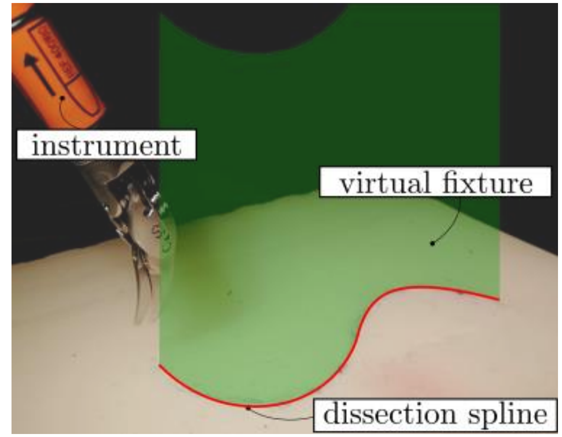


M. Selvaggio et al. “Passive Task-Prioritized Shared-Control Teleoperation with Haptic Guidance”, ICRA 2019

Shared control architectures for surgical applications

Adaptive virtual fixtures





Problem: enhance precision and reduce the operator's workload during surgical dissection tasks

Solution: passive virtual fixtures generation/adaptation architecture

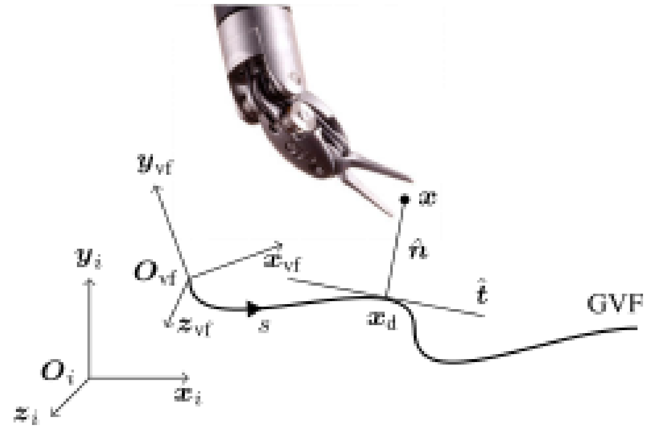
Results: safe interaction with a variable impedance master interface

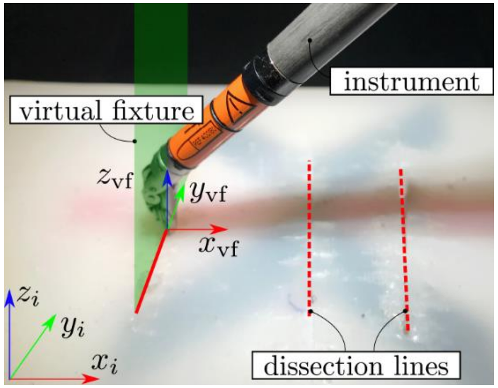
M. Selvaggio et al. "Passive virtual fixtures adaptation in minimally invasive robotic surgery", RAL 2018

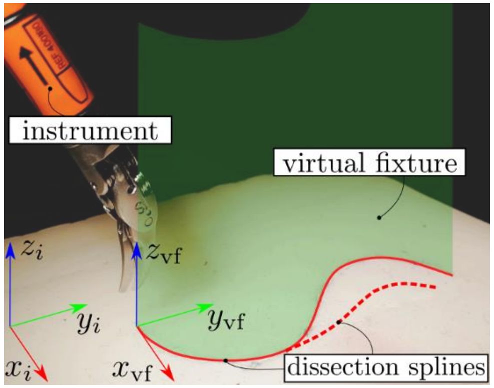
Adaptive virtual fixtures

Features

- Interactive generation using interaction points or vision-based techniques
- Haptic guidance implementation through impedance control
- Interactive pose and geometry adaptation strategies





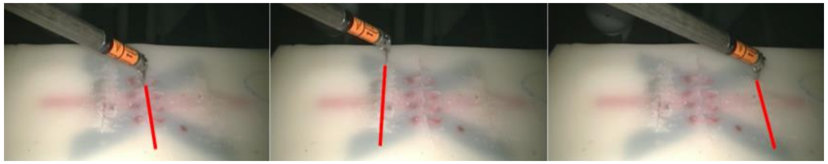


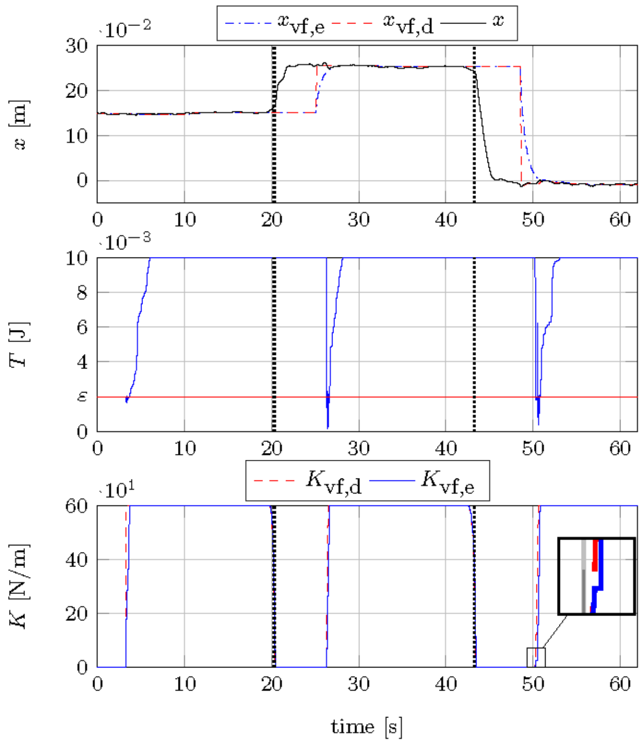
M. Selvaggio et al. "Passive virtual fixtures adaptation in minimally invasive robotic surgery", RAL 2018

Adaptive virtual fixtures

Results

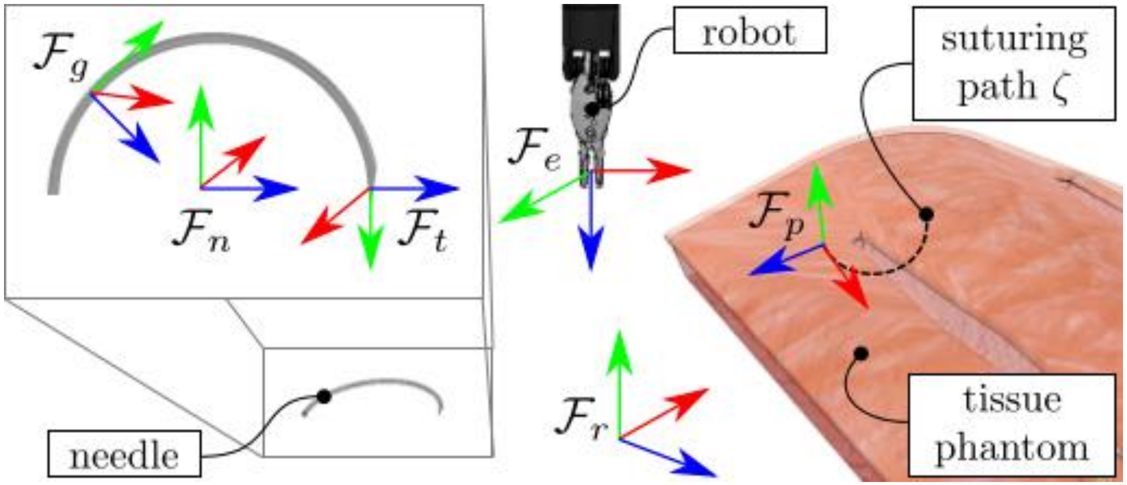
- Semi-autonomous pose and geometry adaptation experiments
- Passivity-based control to keep the variable impedance robotic system safe
- Enhanced precision in performing surgical dissection tasks





M. Selvaggio et al. "Passive virtual fixtures adaptation in minimally invasive robotic surgery", RAL 2018

Haptic-guided optimal needle grasping



Collaboration with

UNIVERSITY OF LINCOLN

Problem: reduce the operator's hand-off movements during suturing tasks

Solution: optimal needle grasping to avoid post-grasping constraints

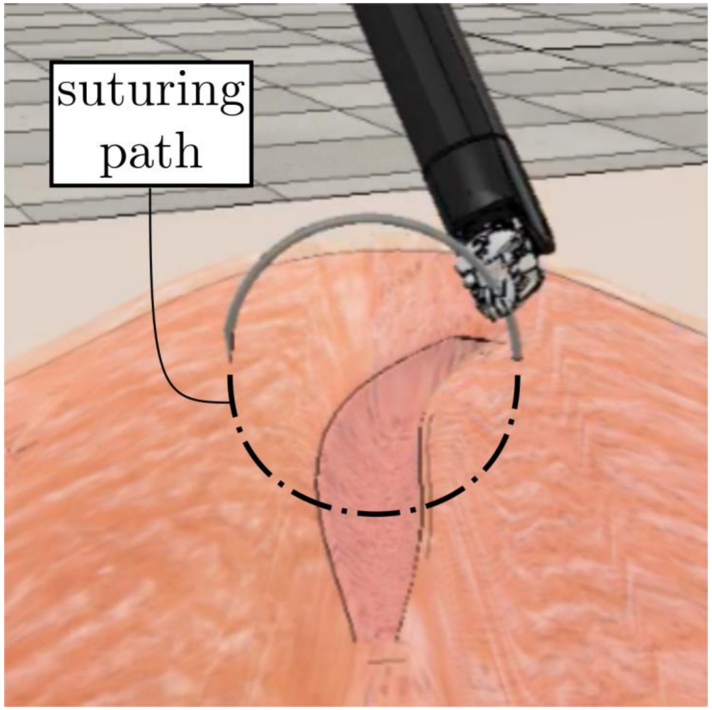
Results: optimal grasping reduces hand-off movements

M. Selvaggio et al. "Needle grasping optimization in minimally invasive robotic surgery using haptic shared control", IROS 2019

Haptic-guided optimal needle grasping

Features

- Needle grasping optimization is used to avoid constraints along the suturing path
- Joint limits and singularities are considered as constraints
- Haptic guidance is used to suggest the user the optimal grasping configuration



M. Selvaggio et al. “Needle grasping optimization in minimally invasive robotic surgery using haptic shared control”, IROS 2019

Haptic-guided optimal needle grasping

Cost function

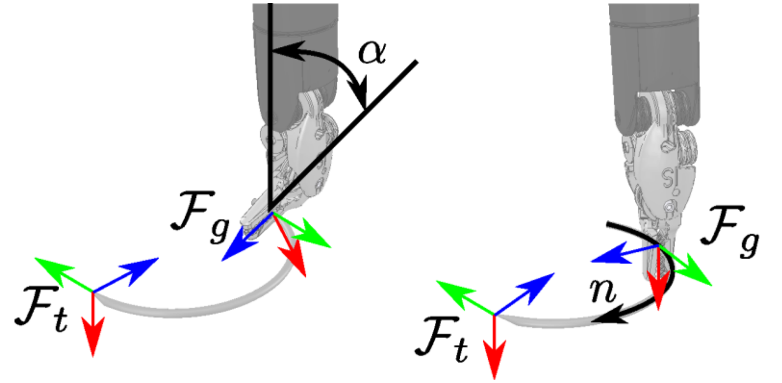
- Joint limits
- Task-oriented manipulability

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

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

Grasp parametrization

- Angle around the needle tangent
- Curvilinear abscissa

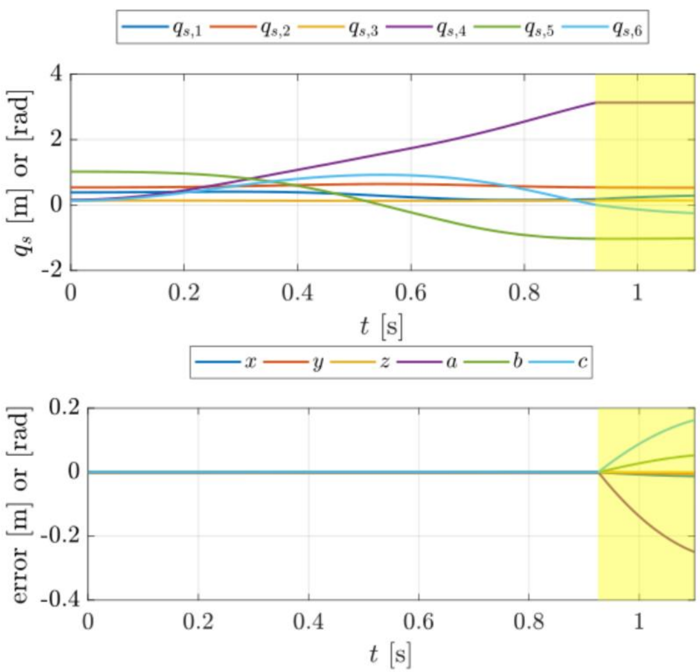


M. Selvaggio et al. “Needle grasping optimization in minimally invasive robotic surgery using haptic shared control”, IROS 2019

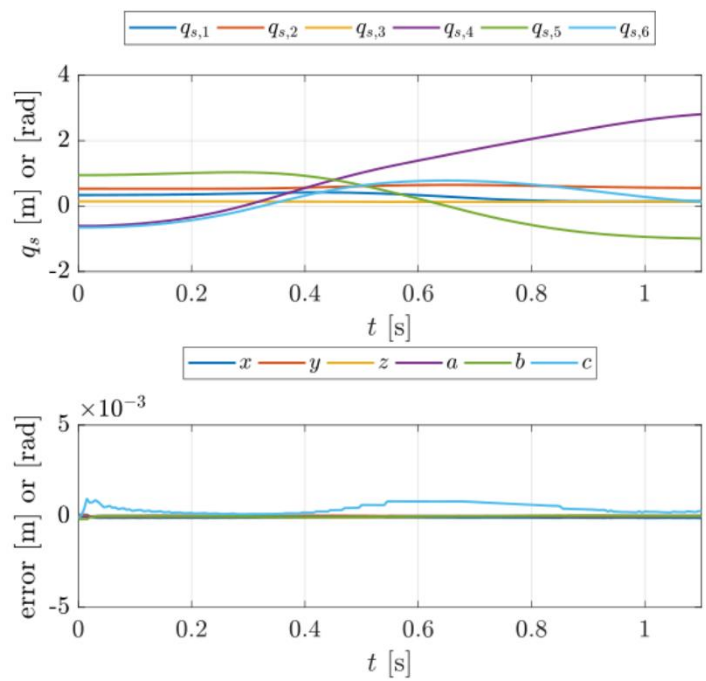
Haptic-guided optimal needle grasping

Experiments

Joint limits

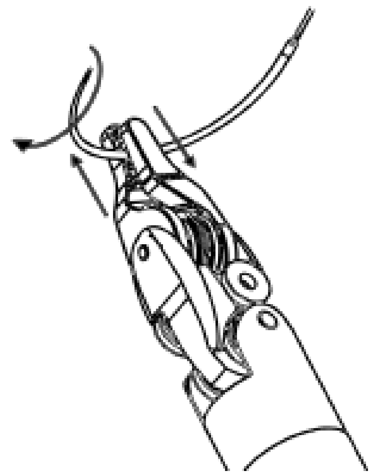


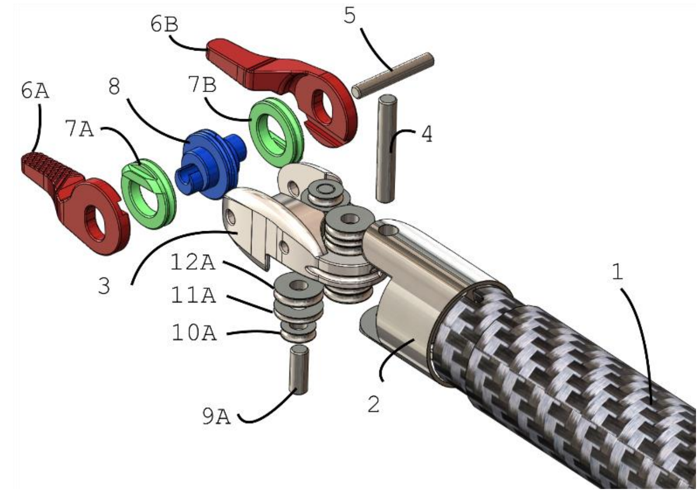
Optimized solution



M. Selvaggio et al. “Needle grasping optimization in minimally invasive robotic surgery using haptic shared control”, IROS 2019

A new laparoscopic tool





Problem: increase dexterity of surgical instruments

Solution: additional DoF for in-hand manipulation

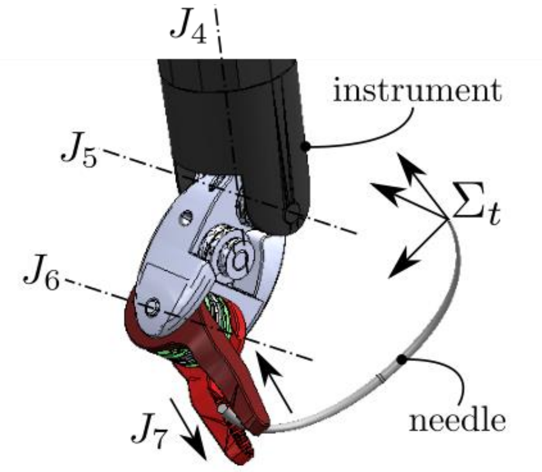
Results: mechanical design and shared-control strategy

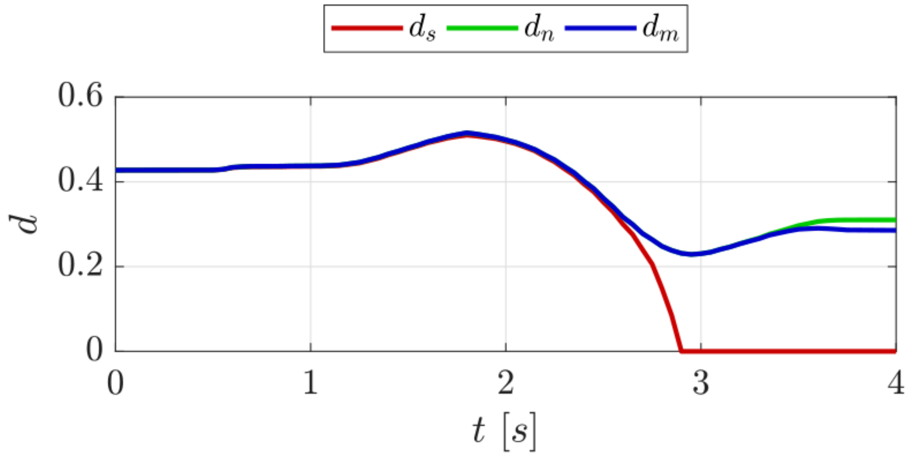
G. A. Fontanelli et al. “A new laparoscopic instrument with in-hand rolling capabilities for needle re-orientation” RAL 2018

A new laparoscopic tool

Features

- Mechanical design of the new tool
- Dexterity measure
- Shared control strategy with autonomous redundancy resolution





M. Selvaggio et al. "Enhancing dexterity with a 7-DoF laparoscopic suturing tool" HSMR 2018

Other activities

The MUSHA hand

Problem: increase dexterity of surgical instruments

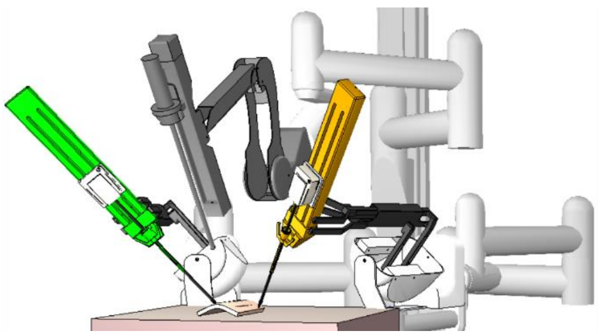
Solution: a novel three-finger hand with tactile sensors

Results: mechanical design, simulation and teleoperation

M. Selvaggio et al. “The MUSHA underactuated hand for robot-aided minimally invasive surgery”, IJMRCAS 2019

H. Liu et al. “The MUSHA hand II: a multi-functional hand for robot-assisted laparoscopic surgery”, TMECH 2019

Simulation



Collaboration with

SAPIENZA
UNIVERSITÀ DI ROMA

Problem: expensive robotic surgical simulators

Solution: development of a V-REP simulation environment

Results: virtual reality, haptic feedback, ROS

iNFORMATION tECHNOLOGY eLECTRICAL eNGINEERING Ph.D

G. A. Fontanelli et al. “A Portable dVRK: an augmented V-REP simulator of the da Vinci Research Kit”, ACTA 2019
M. Ferro et al. “A portable da Vinci simulator in virtual reality”, IRC 2019
G. A. Fontanelli et al. “A V-REP simulator for the da Vinci Research Kit robotic platform”, Biorob 2018

Soft robots

Collaboration with

UCSB

Financially supported by

COINOR

Problem: semi-autonomous teleoperation of soft robots needs reliable model-based planning and control pipelines

Solution: obstacle interaction planning method for vine robots

Results: workspace analysis and planning of interactions paths

ITEE Ph.D INFORMATION TECHNOLOGY ELECTRICAL ENGINEERING

M. Selvaggio et al. “An obstacle-interaction planning method for navigation of actuated vine robots”, ICRA 2020

Products

List of publications

International journal papers

[1] 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 (submitted)*.

[2] G. A. Fontanelli, **M. Selvaggio**, M. Ferro, F. Ficuciello, M. Vendittelli, B. Siciliano, "Portable dVRK: an augmented V-REP simulator of the da Vinci Research Kit", *Acta Polytechnica Hungarica*, vol. 16 (8), pp. 79-98, 2019, DOI: *10.12700/APH.16.8.2019.8.6*.

[3] **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*, vol. 15 (3), pp. 1013-1062, 2019, DOI: 10.1002/rcs.1981.

Products

List of publications

International journal papers

[4] **M. Selvaggio**, F. Chen, D. G. Caldwell, "Dexterous grasping by manipulability selection for mobile manipulator with visual guidance", *IEEE Transactions on Industrial Informatics*, vol. 15 (2), pp. 1202-1210, Feb. 2019, DOI: *10.1109/TII.2018.2879426*.

[5] **M. Selvaggio**, F. Abi-Farraj, C. Pacchierotti, P. Robuffo Giordano, B. Siciliano, "Haptic-based shared-control methods for a dual-arm system", *IEEE Robotics and Automation Letters*, vol. 3 (4), pp. 4249-4256, Oct. 2018, DOI: *10.1109/LRA.2018.2864353*.

[6] **M. Selvaggio**, G. A. Fontanelli, F. Ficuciello, L. Villani, B. Siciliano, "Passive virtual fixtures adaptation in minimally invasive robotic surgery", *IEEE Robotics and Automation Letters*, vol. 3 (4), pp. 3129-3136, Oct. 2018, DOI: *10.1109/LRA.2018.2849876*.

Products

List of publications

International journal papers

[7] G. A. Fontanelli, **M. Selvaggio**, L. R. Buonocore, F. Ficuciello, L. Villani, B. Siciliano, "A new laparoscopic instrument with in-hand rolling capabilities for needle re-orientation", *IEEE Robotics and Automation Letters*, vol. 3 (3), pp. 2354-2361, July 2018, DOI: *10.1109/LRA.2018.2809443*.

[8] S. Grazioso, **M. Selvaggio**, G. Di Gironimo, "Design and development of a novel body scanning system for healthcare applications", *International Journal on Interactive Design and Manufacturing*, vol. 12, pp. 611–620, Aug. 2017, DOI: *10.1007/s12008-017-0425-9*.

Products

List of publications

International conference papers

[1] **M. Selvaggio**, L. A. Ramirez, B. Siciliano, E. W. Hawkes, "An obstacle-interaction planning method for navigation of actuated vine robots", 2020 *IEEE International Conference on Robotics and Automation*, Paris (France), accepted.

[2] G. Notomista, S. Mayya, **M. Selvaggio**, M. Santos, C. Secchi, "A set-theoretic approach to multi-task execution and prioritization", 2020 *IEEE International Conference on Robotics and Automation*, Paris (France), accepted.

[3] **M. Selvaggio**, A. M. Ghalamzan E., R. Moccia, F. Ficuciello, B. Siciliano, "Haptic-guided shared control for needle grasping optimization in minimally invasive robotic surgery", 2019 *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Macau (China), pp. 3617-3623, Nov. 2019, DOI: 10.1109/IROS40897.2019.8968109.

Products

List of publications

International conference papers

[4] R. Moccia, **M. Selvaggio**, L. Villani, B. Siciliano, F. Ficuciello, “Vision-based Virtual Fixtures Generation for Robotic-Assisted Polyp Dissection Procedures”, 2019 *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Macau (China), pp. 7934-7939, Nov. 2019, DOI: 10.1109/IROS40897.2019.8968080.

[5] S. Grazioso, T. Caporaso, **M. Selvaggio**, D. Panariello, R. Ruggiero, G. Di Gironimo, “Using photogrammetric 3D body reconstruction for the design of patient–tailored assistive devices”, *2019 II Workshop on Metrology for Industry 4.0 and IoT*, Naples (Italy), pp. 240-242, June 2019, DOI: 10.1109/METROI4.2019.8792894.

[6] **M. Selvaggio**, P. Robuffo Giordano, F. Ficuciello, B. Siciliano, “Passive task-prioritized shared-control teleoperation with haptic guidance”, *2019 IEEE International Conference on Robotics and Automation*, Monteal (Canada), pp. 430-436, May 2019, DOI: 10.1109/ICRA.2019.8794197.

Products

List of publications

International conference papers

[6] M. Ferro, D. Brunori, F. Magistri, L. Saiella, **M. Selvaggio**, G. A. Fontanelli, “A portable da Vinci simulator in virtual reality”, *2019 Third IEEE International Conference on Robotic Computing*, Naples (Italy), pp. 447-448, Feb. 2019, DOI: 10.1109/IRC.2019.00093.

[7] 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”, *2018 7th IEEE International Conference on Biomedical Robotics and Biomechatronics*, Enschede (The Netherlands), pp. 1056-1061, Aug. 2018, DOI: 10.1109/IRC.2019.00093.

[8] S. Grazioso, M. Gospodarczyk, **M. Selvaggio**, D. Marzullo, G. Di Gironimo, “Eligere: a fuzzy AHP distributed software platform for group decision making in engineering design”, *2017 IEEE International Conference on Fuzzy Systems*, Naples (Italy), pp. 1-6, July 2017, DOI: 10.1109/FUZZ-IEEE.2017.8015713.

Products

List of publications

International conference papers

[9] **M. Selvaggio**, S. Grazioso, G. Notomista, F. Chen, “Towards a self-collision aware teleoperation framework for compound robots”, *2017 IEEE World Haptics Conference*, Veranstaltungsforum Furstenfeld (Germany), pp. 460-465, June 2017, DOI: 10.1109/WHC.2017.7989945.

Products

Awards, prizes, etc.

Scholarships

- **COINOR - STAR L2 program**: scholarship promoted by COINOR - University of Naples Federico II to spend a 6-months abroad period at University of California Santa Barbara.

- **Erasmus+ “Universities for EU projects”**: scholarship promoted by SEND consortium to spend a 2-months abroad period at IRISA, INRIA Rennes.

Grants

- **Innovation in haptics by young researchers**: grant promoted by IEEE RAS Technical Committee on Haptics for the project "Haptic guidance methods for robotic surgery"

Products

Awards, prizes, etc.

Awards

- **Start Cup Campania 2019** - 1° prize with the project INBODY
- **Innovation Village Award 2019** - finalist with the project INBODY, which received the Special Mention "Innovation and Safety" from INAIL
- **Switch 2 Product** - Innovation in Bioengineering: awarded second prize at the Sixth National Congress of Bioengineering with the project MUSHA
- **IEEE-RAS 1st "Robotics Made in Italy" video contest** - second prize award promoted by Italian chapter of the IEEE Robotics and Automation Society

Technology transfer

- **Co-founder of BeyondShape** – University of Naples Federico II Spin off company

Products

Awards, prizes, etc.

Workshops

- **Co-organizer** of the workshop ‘Shared autonomy: learning and control’ to be held at the 2020 IEEE International Conference on Robotics and Automation