Research Topics

Introduzione generale:
Le ricerca del Dipartimento di Eccellenza in Robotics & AI convolge un numero considerevole di docenti e ricercatori (circa l'80% del personale afferente ai tre Istituti che vi partecipano) ed ha prodotto nel corso del primo periodo di finanziamento (2018-2022) numerose linee di ricerca sulla Robotica e l'intelligenza artificiale nei settori di AI e Scienze dei materiali.

Di seguito elenchiamo la lista dei temi di ricerca ai quali afferiscono gruppi di ricercatori sia interni che di altre università, e che hanno partecipato al raggiungimento di risultati scientifici nel corso di questo periodo. Per ciascuno dei temi inoltre, è disponibile una descrizione (esclusivamente in lingua inglese) dei contenuti del tema di ricerca, del team iniziale di lavoro e dei risultati scientifici pubblicati (circa 400) recentemente:

[Creare quindi le due liste seguenti, e una serie di pagine linkate alle voci, per ciascuno tema di ricerca]

Research on AI

1. Safe and Secure AI
2. Time-predictability in the execution of AI workload
3. Efficient Acceleration of Deep Neural Networks
4. 5G Support for AI offloading
5. Photonic Neural-Networks
6. Transient myolectric signal for the prosthetic control
7. The myokinetic control interface
8. Design and assessment of bio-inspired control algorithms for human robot collaboration
9. Design of a Liquid Handling Robot (LHR) with embedded AI algorithms
10. Improvement, development, and application of neural interfaces
11. Application of robotics to restore physiological impairment
12. Analysis of neural, muscular and kinematic data for clinical applications
13. Machine Learning in Industrial Process
14. Deep Learning in Industrial Applications
15. AI for metallurgic science
16. AI Data Analytics for industry
17. Multi Agent Systems for industrial applications
18. Robotics application for the Metallurgical sector
19. Deploy AI & Big Data in process industry
20. AI for industrial quality inspection
21. Vision based flexible robotic manipulation for industry
22. Robotics and AI augmented human assistance and surveillance for health and safety
23. Driverless and autonomous mobile systems
24. Smart mobile localization and tracking
25. Industrial Maintenance and Maintenance on Condition
26. Path planning algorithms for robotics disinfection
27. AI for intuitive control of exoskeleton based on motion intention detection and muscle synergies extraction
28. Ethorobotics as a novel translational neuroethological engineering approach to turn findings into outcomes within real-world healthcare contexts
29. Animal-robot interaction paradigm to face engineering and environmental challenges through sustainable strategies
30. Natural intelligence for bioinspired computing and eco-friendly ecosystem management methods
31. Novel Human-centered control approaches in Industry 4.0 context: special focus on welding process

32. AI and data science strategies for tactile sensing and augmenting haptic feedback with applications to bionic prostheses, healthcare technologies, collaborative robotics and industry 4.0

Research on Smart Materials

1. Integration of FBG sensors in robotics
2. Development of FBG sensors reading units
3. Electrostatic bellow muscle actuators
4. Dielectric elastomers transducers for actuation and energy harvesting
5. Electro adhesive gripper based on thin film dielectrics
6. Development of exoskeleton systems for teleoperation assistance
7. Soft Exosuit and Elastic joints
8. Integration of innovative sensors in mechanical systems
9. Design of wearable haptic devices
10. Testing different coatings to ensure stability and in vivo safety of NdFeB magnets implanted in muscles in a myokinetic control interface
11. Mechanics and Geometry of Smart Materials for Shape Morphing and Sensing
12. New class of biodegradable biohybrid agents with microorganism-based energy harvesting processes for environmental monitoring
13. Investigating locomotion, ultra-structures, and biochemical features of living organisms for robotics and biomedical implementations
14. Physical soft simulators and artificial organs
15. Soft continuous arms and grippers
16. Soft mechatronic technologies
17. Shape programming for smart materials and deployable structures
18. Design principles for bio-inspired microrobots: a two-way interaction between biology and engineering
19. Implantable, wearable and portable mechano-electrotransducers
20. Smart materials for endowing biomedical devices with enhanced properties
21. Wearable Robotics: design, development, and validation of novel exoskeletons and lower-limb prostheses

Safe and Secure AI

Principal investigator: Giorgio Buttazzo and Alessandro Biondi

Collaborators: Daniel Casini, Giulio Rossolini, Federico Nesti, Saasha Nair, Giorgiomaria Cicero, Federico Pacini, Fabio Brau

Description

Although current Deep Neural Networks can achieve super-human performance in image classification and object detection, they are prone to adversarial attacks and can fail when receiving corner-case inputs or inputs that are quite different from those used for the training phase. These issues pose severe questions on the applicability of Deep Learning components in safety-critical systems, such as autonomous cars. Furthermore, DDNs and their related inference engines are complex and large software systems that make the overall system more vulnerable to cyber-attacks.

Our research aims at investigating methodologies and developing techniques that can make Deep Neural Network more robust against cyber-attacks and more safe with respect to corner cases that are difficult to identify during testing. Research is also performed on software architectures to enable the control of safety-critical systems by means of Deep Neural Networks, while also offering high-criticality fallback control functionalities that can take over whenever the AI fails or is attacked. These software architectures have been applied to a real-world autonomous driving framework.

Related publications

1. Federico Nesti, Giulio Rossolini, Saasha Nair, Alessandro Biondi, and Giorgio Buttazzo, "Evaluating the Robustness of Semantic Segmentation for Autonomous Driving against Real-World Adversarial Patch Attacks", Proc. of the Winter Conf. on Applications of Computer Vision (WACV), Waikoloa, Hawaii, Jan 4-8, 2022.
2. Luca Belluardo, Andrea Stevanato, Daniel Casini, Giorgiomaria Cicero, Alessandro Biondi, and Giorgio Buttazzo, "A multi-domain software architecture for safe and secure autonomous driving", Proc. of the 27th IEEE International Conference on Embedded and Real-Time Computing Systems and Applications (RTCSA 2021), Online event, August 18-20, 2021.
3. Federico Nesti, Alessandro Biondi, and Giorgio Buttazzo, "Detecting Adversarial Examples by Input Transformations, Defense Perturbations, and Voting", IEEE Transactions on Neural Networks and Learning Systems, to appear. Also in arXiv:2101.11466 [cs.CV], January 2021.
4. Giulio Rossolini, Alessandro Biondi, and Giorgio Buttazzo, "Increasing the Confidence of Deep Neural Networks by Coverage Analysis", arXiv:2101.12100 [cs.LG], January 2021.
5. Marco Pacini, Federico Nesti, Alessandro Biondi and Giorgio Buttazzo, "X-BaD: A Flexible Tool for Explanation-Based Bias Detection", Proc. of the IEEE International Conference on Cyber Security and Resilience (Virtual), July 26-28, 2021.
6. Alessandro Biondi, Federico Nesti, Giorgiomaria Cicero, Daniel Casini, and Giorgio Buttazzo, "A Safe, Secure, and Predictable Software Architecture for Deep Learning in Safety-Critical Systems", IEEE Embedded Systems Letters, Volume 12, Issue 3, September 2020.
7. Giulio Rossolini, Alessandro Biondi, and Giorgio Buttazzo, "Increasing the Confidence of Deep Neural Networks by Coverage Analysis", arXiv:2101.12100 [cs.LG], January 2021.
8. Federico Nesti, Alessandro Biondi, and Giorgio Buttazzo, "Detecting Adversarial Examples by Input Transformations, Defense Perturbations, and Voting", arXiv:2101.11466 [cs.CV], January 2021.
9. Saasha Nair, Sina Shafaei, Daniel Auge, and Alois Knoll, "An Evaluation of “Crash Prediction Networks” (CPN) for Autonomous Driving Scenarios in CARLA Simulator", Proceedings of the Workshop on Artificial Intelligence Safety 2021 (SafeAI 2021) co-located with the Thirty-Fifth AAAI Conference on Artificial Intelligence (AAAI 2021) Virtual, February 8, 2021.

Time-predictability in the Execution of AI Workload

Principal investigator: Alessandro Biondi

Collaborators: Daniel Casini, Francesco Restuccia, Giorgio Buttazzo

Description

AI-based cyber-physical systems must also comply with stringent timing and safety constraints to ensure a proper interaction with the physical world. An AI-based critical system that is not capable of reacting within predetermined and predictable temporal deadlines cannot be simply deemed safe. For instance, this requirement is essential in autonomous driving systems.

Our research focuses on analytical techniques and run-time mechanisms capable of improving the time-predictability of AI workload. In particular, complex parallel workloads as those generated by the popular TensorFlow machine learning framework have been analyzed and supported by new techniques to enable a time-predictable execution. Components and analysis methods have also been developed for AI hardware accelerators deployed on FPGA fabrics.

Related publications

1. Daniel Casini, Alessandro Biondi, and Giorgio Buttazzo, "Timing Isolation and Improved Scheduling of Deep Neural Networks for Real-Time Systems", Software: Practice and Experience, Volume 50, Issue 9, September 2020.
2. Daniel Casini, Alessandro Biondi, and Giorgio Buttazzo, "Analyzing Parallel Real-Time Tasks Implemented with Thread Pools", In Proceedings of the 56th ACM/ESDA/IEEE Design Automation Conference (DAC 2019), Las Vegas, NV, USA, June 2-6, 2019.
3. Francesco Restuccia, Alessandro Biondi, Mauro Marinoni, Giorgiomaria Cicero, and Giorgio Buttazzo, "AXI HyperConnect: A Predictable, Hypervisor-level AXI Interconnect for Hardware Accelerators in FPGA SoC", In Proceedings of the 57th ACM/ESDA/IEEE Design Automation Conference (DAC 2020), San Francisco, CA, USA, July 19-23, 2020.
4. Francesco Restuccia and Alessandro Biondi, "Time-Predictable Acceleration of Deep Neural Networks on FPGA SoC Platforms", In Proceedings of the 42nd IEEE Real-Time Systems Symposium (RTSS 2021), Dortmund, Germany, December 7-10, 2021.
5. Francesco Restuccia, Marco Pagani, Alessandro Biondi, Mauro Marinoni, and Giorgio Buttazzo, "Modeling and Analysis of Bus Contention for Hardware Accelerators in FPGA SoCs", In Proceedings of the 32nd Euromicro Conference on Real-Time Systems (ECRTS 2020), July 7-10, 2020.
6. Daniel Casini, Alessandro Biondi, and Giorgio Buttazzo, "Analyzing Parallel Real-Time Tasks Implemented with Thread Pools", Proc. of the 56th ACM/ESDA/IEEE Design Automation Conference (DAC 2019), Las Vegas, NV, USA, June 2-6, 2019.
7. Daniel Casini, Alessandro Biondi, and Giorgio Buttazzo, "Deep Neural Networks for Safety-Critical Applications: Vision and Open Problems", Proc. of the 9th Int. Real-Time Scheduling Open Problems Seminar (RTSOPS 2018), Barcelona, Spain, July 3, 2018 (Best paper award).

Efficient Acceleration of Deep Neural Networks

Principal investigator: Alessandro Biondi

Collaborators: Marco Pagani, Biruk Seyoum, Francesco Restuccia, Giorgio Buttazzo

Description

The emergence of AI-based cyber-physical systems, such as autonomous cars and advanced robots, is posing new challenges related to the acceleration of machine learning algorithms on resource-constrained, embedded devices. This calls for new methodologies and technologies to properly address the integration of AI in such systems.

Our research focuses on methodologies to efficiently accelerate Deep Neural Network using the FPGA technology, which is capable of providing *high energy efficiency* while retaining flexibility and high performance. This research is particularly relevant considering the environmental impact that billions of AI-enabled devices spread on a multitude of applications can have in the near future. Indeed, even with today's limited applications of AI in our society, the energy consumption of AI-enabled devices already established as one of the major problems to be solved. This research is also contributing to the AMPERE European project funded by the Horizon 2020 programme.

Related publications

1. Alessandro Biondi, Daniel Casini, Giorgiomaria Cicero, Niccolò Borgioli, Giorgio Buttazzo, et al., "SPHERE: A Multi-SoC Architecture for Next-generation Cyber-Physical Systems Based on Heterogeneous Platforms", IEEE Access, Vol. 9, pp. 75446-75459, May 2021.
2. Biruk Seyoum, Marco Pagani, Alessandro Biondi, Sara Balleri, and Giorgio Buttazzo, "Spatio-Temporal Optimization of Deep Neural Networks for Reconfigurable FPGA SoCs", IEEE Transactions on Computers, Volume 70, Issue 11, 2021.
3. Biruk Seyoum, Alessandro Biondi, Marco Pagani, and Giorgio Buttazzo, "Automating the Design Flow under Dynamic Partial Reconfiguration for Hardware-Software Co-design in FPGA SoC", In Proceedings of the 36th ACM/SIGAPP Symposium on Applied Computing (SAC 2021), March 22-26, 2021.

5G support for AI offloading

Principal investigator: Piero Castoldi

Collaborators: Luca Valcarenghi, Andrea Sgambelluri, Gabriele Cecchetti, Francesco Paolucci, Justine C. Borromeo, Davide Scano, Barbara Martini (CNIT), Filippo Cugini (CNIT)

Description

Edge computing can dramatically improve services and applications by supporting artificial intelligence (AI) natively, instead of relying on AI in the cloud. Edge computing that supports AI (without cloud intervention) is the most promising technology that will enable many of the long-awaited advanced connected services: Factory 4.0 and intelligent manufacturing, true Internet of Things, self-driving vehicles, remote robotics for assistance healthcare, tele-presence systems, and many others.
The introduction of AI into edge computing is not just a software implementation process; specific hardware must be designed with big data processing and artificial intelligence in mind. The main objective of this research line is to develop an Edge Computing infrastructure that offers 5G control, processing, acceleration, storage and networking at the edge and has excellent performance in terms of scalability, agility, security, low-latency and mission-critical systems.

Related publications

1. Borromeo, J.C., Kondepu, K., Fichera, S., Castoldi, P., Valcarenghi, L. Experimental Demonstration of Scalable and Low Latency Crowd Management Enabled by 5G and AI in an Accelerated Edge Cloud Optical Fiber Communications Conference and Exhibition, OFC 2021 - Proceedings.
2. Paolucci, F., Cugini, F., Castoldi, P., Osinski, T. Enhancing 5G SDN/NFV Edge with P4 Data Plane Programmability (2021) IEEE Network, 35 (3), pp. 154-160.
3. Paolucci, F., Scano, D., Cugini, F., Sgambelluri, A., Valcarenghi, L., Cavazzoni, C., Ferraris, G., Castoldi, P. User Plane Function Offloading in P4 switches for enhanced 5G Mobile Edge Computing 17th International Conference on the Design of Reliable Communication Networks, DRCN 2021.
4. Venkatarami Reddy Chintapalli, Koteswararao Kondepu, Andrea Sgambelluri, Bheemarjuna Reddy Tamma, Piero Castoldi, Luca Valcarenghi, “Orchestrating Edge-and Cloud-based Predictive Analytics Services”, 2020 European Conference on Networks and Communications (EuCNC), June 2020
5. Cugini, F., Scano, D., Giorgetti, A., Sgambelluri, A., Castoldi, P., Paolucci, F. P4 Programmability at the Network Edge: The BRAINE Approach [Invited] Proceedings - International Conference on Computer Communications and Networks, ICCCN, 2021-July
6. Civerchia, F., Sgambelluri, A., Paolucci, F., Maggiani, L., Castoldi, P., Cugini, F. Hardware acceleration for Processing Function Virtualization IEEE International Mediterranean Conference on Communications and Networking, MeditCom 2021, pp. 47-51.
7. Borromeo, J.C., Kondepu, K., Fichera, S., Castoldi, P., Valcarenghi, L. Experimental demonstration of scalable and low latency crowd management enabled by 5G and AI in an accelerated edge cloud (2021) Optics InfoBase Conference Papers, .
8. Sambo, N., Fichera, S., Sgambelluri, A., Fioccola, G., Castoldi, P., Katsalis, K. Enabling Delegation of Control Plane Functionalities for Time Sensitive Networks (2021) IEEE Access, 9, pp. 136151-136163.
9. Gharbaoui, M., Martini, B., Cecchetti, G., Castoldi, P. Resource Orchestration Strategies with Retrials for Latency-Sensitive Network Slicing over Distributed Telco Clouds (2021) IEEE Access, 9, pp. 132801-132817.
10. Federico Civerchia, Francesco Giannone, Koteswararao Kondepu, Piero Castoldi, Luca Valcarenghi, A Bragagnini, F Gatti, A Napolitano, Justine Cris Borromeo, “Remote Control of a Robot Rover Combining 5G, AI, and GPU Image Processing at the Edge”, Proc. of OFC 2020, 8–12 March 2020, San Diego, California, United States
11. Francesco Paolucci, Filippo Cugini, Piero Castoldi, Tomasz Osinski, “Enhancing 5G SDN/NFV Edge with P4 Data Plane Programmability”, April 2021, IEEE Network, pag 1-7

12. Francesco Paolucci, Davide Scano, Filippo Cugini, Andrea Sgambelluri, Luca Valcarenghi, Carlo Cavazzoni, Giuseppe Ferraris, Piero Castoldi, “User Plane Function Offloading in P4 switches for enhanced 5G Mobile Edge Computing”, Proc. of DRCN 2021, April 2021, Milan, Italy.
13. Molka Gharbaoui, Barbara Martini, Piero Castoldi, “Implementation of an Intent Layer for SDN-enabled and QoS-Aware Network Slicing”, accepted for presentation at International Workshop on Intent-Based Networking (WIN'2021), in conjunction with IEEE Netsoft 2021, June 28, 2021 // Tokyo, Japan
14. Scano, D., Paolucci, F., Kondepu, K., Sgambelluri, A., Valcarenghi, L., Castoldi, P., Cugini, F. Augmented In-Band Telemetry to the User Equipment for beyond 5G Converged Packet-Optical Networks European Conference on Optical Communications, ECOC 2020.
15. Civerchia, F., Kondepu, K., Borromeo, J.C., Sambo, N., Castoldi, P., Valcarenghi, L. A Fast and Low Capacity Virtual RAN Recovery based on PDCP Split and Optical Fronthaul Traffic Filtering IEEE 3rd 5G World Forum, 5GWF 2020 - Conference Proceedings, pp. 430-435.
16. Martini, B., Mori, P., Marino, F., Saracino, A., Lunardelli, A., Marra, A.L., Martinelli, F., Castoldi, P. Pushing Forward Security in Network Slicing by Leveraging Continuous Usage Control IEEE Communications Magazine, 58 (7), pp. 65-71.
17. Reddy Chintapalli, V., Kondepu, K., Sgambelluri, A., Franklin A, A., Reddy Tamma, B., Castoldi, P., Valcarenghi, L. Orchestrating edge- And cloud-based predictive analytics services European Conference on Networks and Communications, EuCNC 2020, pp. 214-218.
18. Civerchia, F., Pelcat, M., Maggiani, L., Kondepu, K., Castoldi, P., Valcarenghi, L. Is OpenCL Driven Reconfigurable Hardware Suitable for Virtualising 5G Infrastructure? (2020) IEEE Transactions on Network and Service Management, 17 (2), pp. 849-863.
19. Gharbaoui, M., Martini, B., Castoldi, P. Programmable and Automated Deployment of Tenant-Managed SDN Network Slices Proceedings of IEEE/IFIP Network Operations and Management Symposium 2020: NOMS 2020.
20. Civerchia, F., Giannone, F., Kondepu, K., Castoldi, P., Valcarenghi, L., Bragagnini, A., Gatti, F., Napolitano, A., Borromeo, J.C. Remote Control of a Robot Rover Combining 5G, AI, and GPU Image Processing at the Edge Optical Fiber Communications Conference and Exhibition, OFC 2020 - Proceedings.

Photonic Neural Networks

Principal investigator: Giampiero Contestabile and Piero Castoldi

Collaborators: Piero Castoldi, Lorenzo De Marinis, Nicola Andriolli (CNR), Marco Cococcioni (UNIPI)

Description

Photonic solutions for communication and optical processing have evolved with the aim of increasing transmission speed and energy efficiency compared to equivalent electronic systems. For this reason, implementations of optical neural networks (Photonic Neural Networks, PNN) are attractive because they can exploit the great parallelism (through degrees of freedom such as wavelength, signal polarization and transmission mode) and high connectivity obtainable with optics.
In this research line, all-optical processing structures supporting acceleration of neural network computation are investigated. Different optical implementation of the linear processing component in neural networks are assessed and improved against their numerical precision in terms of bits. The problems of interfacing these photonic accelerators with the non-linear electronic or emulated components of the neural network are addressed.

Related publications

1. Andriolli, N., Giorgetti, A., Castoldi, P., Cecchetti, G., Cerutti, I., Sambo, N., Sgambelluri, A., Valcarenghi, L., Cugini, F., Martini, B., Paolucci, F. Optical networks management and control: A review and recent challenges (2022) Optical Switching and Networking, vol. 44.
2. De Marinis, L., Cococcioni, M., Liboiron-Ladouceur, O., Contestabile, G., Castoldi, P., Andriolli, N. Photonic integrated reconfigurable linear processors as neural network accelerators (2021) Applied Sciences (Switzerland), 11 (13).
3. Paolucci, F., De Marinis, L., Castoldi, P., Cugini, F. Demonstration of P4 Neural Network Switch Optical Fiber Communications Conference and Exhibition, OFC 2021 - Proceedings.
4. Gharbaoui, M., Martini, B., Castoldi, P.Implementation of an Intent Layer for SDN-enabled and QoS-Aware Network Slicing Proceedings of the 2021 IEEE Conference on Network Softwarization: Accelerating Network Softwarization in the Cognitive Age, NetSoft 2021, pp. 17-23.
5. Sgambelluri, A., Pacini, A., Paolucci, F., Castoldi, P., Valcarenghi, L. Reliable and scalable Kafka-based framework for optical network telemetry (2021) Journal of Optical Communications and Networking, 13 (10), pp. E42-E52
6. Lorenzo De Marinis, Marco Cococcioni, Piero Castoldi, Nicola Andriolli, “Photonic neural networks: a survey”, IEEE Access, Dec. 2019, Volume 7, Pages 175827-175841
7. Lorenzo De Marinis, Marco Cococcioni, Odile Liboiron-Ladouceur, Giampiero Contestabile, Piero Castoldi, and Nicola Andriolli “Photonic Integrated Reconfigurable Linear Processors as Neural Network Accelerators” (Invited paper), MDPI Applied Sciences, submitted.

Transient myoelectric signal for the prosthetic control: movement intention decoding and grip force prediction.

Principal investigator: Christian Cipriani

Collaborators: Daniele D'Accolti, Francesco Clemente, Andrea Mannini, Itzel Jared Rodriguez Martinez, Marco Controzzi, Gunter Kanitz.

Description

We propose an approach for decoding the intended grasp and grip force from the forearm EMGs by processing the signals associated with the onset of muscle contraction. As grasping largely relies on feedforward mechanisms we hypothesized that the muscle contractions associated with the initial phase of the grasp contained predictive information about the intended preplanned grasp and the correspondent grasp force.
Concerning grasp force estimation, initial offline study included 12 healthy subjects performing a pick-and-lift task. With our methodology, estimations of the grasp force through 16 EMG channels reached an absolute error of 2.52% the maximum voluntary force using only transient information and 1.99% with the first 500 ms of data following the onset. The final GF estimation from transient EMG was comparable to the one obtained using steady state data, confirming our hypothesis that the transient phase contains information about the final GF. A successive online study was conducted with both 12 non-amputees and five amputees. The predictive algorithm was tested during a pick and lift task (tri-digital grasp) with light objects (200 g – 1 kg), for which fine control of the grasp force is more important. Results show that, during this task, it is possible to estimate the target grasp force with an absolute error of 2.06 (1.32) % and 2.04 (0.49) % the maximum voluntary force for non-amputee and amputees, respectively.
Regarding the decoding of the intended grasp, we investigated if both wrist and hand intended movements could be decoded from the transient phase of the myoelectric signal. Twelve healthy individuals performed one of four grasps and of five wrist movements simultaneously (20 combinations). Albeit the performance in recognizing both movements simultaneously was poor with and overall accuracy of 58.86 %, the offline data analysis showed the feasibility of implementing a sequential wrist-hand embedded controller based on the transient phase with an overall accuracy of 89.54 %. The sampling frequency and length of the classified EMG window that off-line resulted in optimal performance were applied to a controller of a research prosthesis worn by one hand amputee and proved functional in real-time when operated under realistic working conditions.
Both analysed approaches would allow for a biomimetic control of a prosthetic hand. Indeed, the users could contract their muscles only once before the grasp begins with no need to modulate the grasp force or maintain a specific contraction pattern for the whole duration of the grasp, as required with continuous dexterous classifiers based on pattern recognition. These results pave the way to fast, intuitive and robust myoelectric controllers of limb prostheses.

Related publications

1. Kanitz, G., Cipriani, C., & Edin, B. B. (2018). Classification of transient myoelectric signals for the control of multi-grasp hand prostheses. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *26*(9), 1756-1764.
2. D'Accolti, D., Mannini, A., Clemente, F., & Cipriani, C. (2020, July). CLASSIFICATION OF TRANSIENT MYOELECTRIC SIGNALS FOR THE CONTROL OF MULTI-GRASP WRIST-HAND PROSTHESIS. In *MEC Symposium Conference*.
3. Martinez, I. J. R., Clemente, F., Kanitz, G., Mannini, A., Sabatini, A. M., & Cipriani, C. (2018, August). Grasp Force Estimation from HD-EMG Recordings with Channel Selection Using Elastic Nets: Preliminary Study. In *2018 7th IEEE International Conference on Biomedical Robotics and Biomechatronics (Biorob)* (pp. 25-30). IEEE.

4. Martinez, I. J. R., Mannini, A., Clemente, F., Sabatini, A. M., & Cipriani, C. (2020). Grasp force estimation from the transient EMG using high-density surface recordings. *Journal of neural engineering*, *17*(1), 016052.
5. Martínez, I. J. R., Mannini, A., Clemente, F., & Cipriani, C. (2020). Online Grasp Force Estimation From the Transient EMG. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *28*(10), 2333-2341.

The myokinetic control interface: tracking implanted magnets as a means for prosthetic control.

Principal investigator: Christian Cipriani

Collaborators: Sergio Tarantino, Francesco Clemente, Antonio De Simone, Marco Controzzi, Marta Gherardini, Stefano Milici, Federico Masiero, Andrea Mannini, Valerio Ianniciello, Edoardo Sinibaldi, Francesca Ferrari

Description

We proposed a new HMI that aims to track the muscles contractions with implanted permanent magnets, by means of magnetic field sensors. Indeed, since the magnet would travel with the muscle it is implanted in, its localization would provide a direct measure of the contraction/elongation of that muscle (which is voluntarily controlled by the central nervous system). Generalizing, multiple MMs in multiple muscles, could entail simultaneous, physiologically appropriate, direct control over multiple DoFs. If successful, this approach could have an impact on and beyond trans-radial amputees because it can be extended to all kinds of upper limb and lower limb amputations. Notably, this could be possible using passive implants not requiring a power supply and not subject to electrical failures and maintenance. We called this a *myokinetic control interface*.
We first presented a prototype which exploited six 3-axis magnetic sensors to localize four magnets implanted in a mockup mimicking the forearm anatomy. The system proved highly linear and precise, yet exhibiting short computation delay and limited cross talk errors. Thus, we systematically analysed the effects of different parameters on the accuracy of the localizer, to formulate general guidelines for the implementation of magnetic tracking systems. We observed that the accuracy of the localization was mainly affected by a specific angle θ, descriptive of the system geometry, and we defined a threshold value for θ above which an indefinite high number of magnets can always be accurately tracked. The latter was also assessed by simulating three different levels of below-elbow amputation aided by a 3D CAD model of the forearm. In a distal amputation, we could accurately up to 19 magnets, thus answering the question: “how many magnets could be implanted in a forearm and successfully tracked with a the myokinetic control approach?”.
Regarding the acquisition system, we developed a method to optimize the sensor number and their distribution in space, to boost the system performance without affecting the localization accuracy. We also addressed the role of the intrinsic properties of the sensors, by analysing their effects on the tracking accuracy and on the computation time of the localization algorithm. We observed that the tracking accuracy is primarily affected by the localization rate, which is directly related to the sampling frequency of the sensors, and less significantly affected by the sensor resolution. To make the whole system wearable, we developed an embedded solution able to retrieve online the pose of several magnetic markers using a matrix of 3-axial hall sensors. Compared to the previous Desktop implementation, the system exhibited similar precision and accuracy, while being ~75% faster. We also exploited such system to investigate the influence of different electromagnetic interferences on the localization accuracy, and the results suggested that a shielding strategy may be needed to reject the noise sources encountered in everyday life.

Notably, the *myokinetic interface* could potentially restore not only the efferent information (i.e. the control signals), but also appropriate tactile/proprioceptive (i.e. position) information of a missing finger or DoF. This could be achieved by inducing controlled vibrations on the implanted magnets, which in turn could generate a perceivable stimulus conveyed to the brain by means of the peripheral sensory receptors. Preliminary studies on the feasibility of the approach have already been conducted with stroke patients, by using a wearable neurorobotic proprioceptive feedback system. Kinematic analyses revealed that injecting a 90 Hz illusory kinaesthetic sensation into an actively contracting muscle increased the movement smoothness, directness, and amplitude.
Overall, these studies pave the way towards the development of new human-machine interfaces for controlling artificial limbs, potentially able to restore the sensory-motor control loop following limb amputation.

Related publications

1. Tarantino, S., Clemente, F., Barone, D., Controzzi, M., & Cipriani, C. J. S. R. (2017). The myokinetic control interface: tracking implanted magnets as a means for prosthetic control. Scientific reports, 7(1), 1-11.
2. Tarantino, S., Clemente, F., De Simone, A., & Cipriani, C. (2019). Feasibility of tracking multiple implanted magnets with a myokinetic control interface: simulation and experimental evidence based on the point dipole model. *IEEE Transactions on Biomedical Engineering*, *67*(5), 1282-1292.
3. Gherardini, M., Clemente, F., Milici, S., & Cipriani, C. (2021). Localization accuracy of multiple magnets in a myokinetic control interface. *Scientific Reports*, *11*(1), 1-10.
4. Milici, S., Gherardini, M., Clemente, F., Masiero, F., Sassu, P., & Cipriani, C. (2020). The Myokinetic Control Interface: How Many Magnets Can be Implanted in an Amputated Forearm? Evidence From a Simulated Environment. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *28*(11), 2451-2458.
5. Gherardini, M., Mannini, A., & Cipriani, C. (2021). Optimal Spatial Sensor Design for Magnetic Tracking in a Myokinetic Control Interface. Submit. to *Computer Methods and Programs in Biomedicine*.
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Design and assessment of bio-inspired control algorithms for human robot collaboration.

Principal investigator: Marco Controzzi

Collaborators: Francesca Cini, Angela Mazzeo

Description

Achieving robust, safe, and flexible collaboration between humans and robots where robots will manipulate objects jointly with humans, is the next major challenge in robotics achievable also by means of a proper design of the robot end-effector. Nowadays robots are specifically designed for constrained or restricted sets of tasks in structured environments, and more important are neither designed nor programmed for collaborating fluently with humans. Collaborative robots have the potential to promote the reintegration in the society of disabled people and give them the chance of even going back to their professional life. At home this cooperative robot would provide assistance to the disabled people and elderly in domestic activities as carrying heavy objects, or simply gently passing a bottle of water. To date, Human Robot interaction is unintuitive, restrictive, and limited to a rigid command-and-response fashion. The fundamental challenges that we are facing within this research line are: i) how to build functional and dexterous artificial hands able to share tools and environment designed for human beings; ii) how to enable a fluent, efficient and safe interaction, and iii) how to enable robots to autonomously grasp and manipulate objects of daily life. Tools: Matlab, National Instruments, Creo, Ultimaker S5, Form3. Tasks: i) Design (Creo) and manufacturing (Ultimaker S5, Form3) of the experimental setup and assessment tools. ii) Acquisition (National Instruments) and analysis (Matlab) of the experimental data.

Related publications

1. F. Cini, V. Ortenzi, P. Corke, M. Controzzi, On the choice of grasp type and location when handing over an object Science Robotics, vol. 4, no. 27, eaau9757, 2019. DOI:10.1126/scirobotics.aau9757.
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3. V. Ortenzi, F. Cini, T. Pardi, N. Marturi, R. Stolkin, P. Corke, M. Controzzi, The grasp strategy of a robot passer influences performance and quality of the robot-human object handover, Frontiers in Robotics and AI, 7: 542406, 2020. DOI:10.3389/frobt.2020.542406

Design of a Liquid Handling Robot (LHR) with embedded AI algorithms.

Principal investigator: Marco Controzzi

Collaborators: -

Description

Liquid handling robots are one of the most important elements in laboratory automation. Within this research line, we designed a new pipettor based on a flow sensor and embedded with AI algorithms that allow to autonomously detect the liquid level within the tube, accurately aspirate and dispense liquids within a range of 0.5 to 1000 µL, detect clots or other errors that may affect the process.
Tools: Matlab, National Instruments, Creo, Ultimaker S5, From3, SARIX T1-T4 EDM (Electrical discharge machining), Semiautomatic milling machine 4/5 axis PICOMAX, Instron mod 5965.
Tasks: i) Design (Creo, ANSYS) of the LHR. ii) Prototyping (Ultimaker S5, Form3) and manufacturing of the manifolds (SARIX T1-T4 EDM (Electrical discharge machining), Semiautomatic milling machine 4/5 axis PICOMAX). iii) Assessment of the force-displacement characteristic of the tip adapter (Instron mod 5965). iv) Acquisition (National Instruments) and analysis (Matlab) of the experimental data.

Related publications

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Improvement, development, and application of neural interfaces

Principal investigator: Silvestro Micera

Collaborators: Alberto Mazzoni, Ivo Strauss, Eugenio Redolfi-Riva, Filippo Agnesi, Alice Giannotti, Daniela De Luca, Ciro Zinno, Simone Romeni, Giacomo Valle, Annarita Cutrone, Francesca Dedola, Antonio Renaudo, Jacopo Carpaneto, PierNicola Sergi, Guido Giudetti, Filippo Agnesi, Daniela De Luca, Martina Righi

Description

The development of highly functional neural interfaces is essential to restore physiological functions such as sensory feedback in upper- and lower-limb amputees, cardiovascular functions in heart transplant patients, bladder dysfunction patients, and optical nerve functions. We developed several types of neural electrodes to restore such functions. In particular the following electrodes have been developed: 1) The quick to implant peripheral intraneural electrode (Q-PINE) to restore sensory feedback in lower-limb amputees. This electrodes neural selectivity has been verified in in vitro and in vivo animal experiments implanted within the sciatic nerve. 2) the tf-QPINE, an extended and improved version of the Q-PINE adapted for the stimulation and the recording of the vagus nerve. This device has been tested in vitro so far. 3) The regenerative active neural interface (RAI) which has been shown to regenerate the sciatic nerve of the rat in in vivo experiments. 4) The VRAI, which is an adapted version of the RAI for the thoracic VN to restore cardiac functions in heart transplant patients. The VRAIs biocompatibility has been increased by introducing a highly biocompatible regenerative channel made of chitosan and polycaprolactone (PCL). The Chitosan@PCL regenerative channel will allow stable anchorage for the VRAI electrode, as well as it will provide a safe and appropriate environment for vagus nerve regeneration. The materials have been designed to be also biodegradable, thus to avoid the risk of a second surgery to remove the implant. 5) The three-dimensional self-opening intraneural peripheral interface (SELINE) which has been tested extensively in the rats sciatic nerve showing high neural selectivity and good biocompatibility over long-term. And has also been shown to function as a visual prosthesis in rabbits.
The here presented devices have been developed using state of the art technologies. Furthermore all designs have been based on histological data obtained from literature or nerve explantations. This step is essential to guarantee the success of the device. Additionally the development of mechanical and electrical nerve models has been part of the electrode development procedures. Doing so, predictions about the neural selectivity and the applied forces (during and after the implantation) could be predicted and optimized. High biocompatibility has been carefully evaluated in vitro using materials such as Chitosan, electro-spun silk, and other coatings. In vitro tests were performed to assure high biocompatibility before implanting the devices. To assure the electrodes electrical function, electrochemical tests such as impedance measurements, cyclic voltammetry and voltage transient measurements were performed prior to each implantations. To increase the electrochemical performance of the here presented devices, additional coatings such as Iridium Oxide, poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT), and Platinum Nanograss (PTNG) have been introduced.

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Application of robotics to restore physiological impairment

Principal investigator: Silvestro Micera

Collaborators: Alberto Mazzoni, Ivo Strauss, Maria Pasquini, Marina Cracchiolo, Federica Barberi, Sara Conti, Giacomo Valle, Fiorenzo Artoni, Federica Aprigliano, Vito Monaco, Jacopo Carpaneto, Alessandro Panarese, Michael Lassi, Elena Losanno

Description

We developed and tested a range of neuroprosthetic devices aiming at restoring functions lost due to a variety of neurological disorders or neurotraumatic lesions. The fields of application were:

I. Neural stimulation studies to restore sensation in upper limb amputees. These included restoring of tactile sensation through biomimetic stimulation and the study of the long term effects of such stimulations, in terms for instance of perceived area of perception localization in the phantom limb and cognitive load required.
II. Stroke rehabilitation studies focusing on motor control restoration.
III. Studies on monitoring the rehabilitation of gait, also with the use of wearable sensors.

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Analysis of neural, muscular and kinematic data for clinical applications

Principal investigator: Silvestro Micera

Collaborators: Alberto Mazzoni, Vito Monaco, Jacopo Carpaneto, Giacomo Valle, Ivo Strauss, Federica Barberi, Fiorenzo Artoni, Marina Cracchiolo, Francesco Iberite, Matteo Vissani, Nicolò Meneghetti, Federica Aprigliano, Annalisa Cutrone, Fabio Vallone, Francesca Dedola.

Description

In the last years the team developed novel tools for the analysis of biological signals such as neural activity at different levels, muscular activity and movements. For each signal we adopted a combination of ad hoc analysis tools and general-purpose strategies from fields as machine learning. The purpose of these analysis was the development of novel therapies for the replacement of missing or altered body functions. As several of these therapies include the need of online decoding of the patient's condition and/or the real time adjustment of neural stimulations, the analysis typically includes very fast decoding of rich datasets as well as modelling for stimulation parameters design and adjustments.
Analysis of neural activity was part of the work on neuroprosthetics (see above) for instance for the decoding motor intention from the activity in the residual nerves or from electromyographic signals in the stump. Most of the studies were based on clinical trials on patients with amputations, but we also analyzed the neural activity of animal models during neural stimulation. Two novel fields of application were the bioelectronic medicine and deep brain stimulation therapies for motor disorders. Bioelectronic medicine aim is to develop novel neuromodulation therapies for pathologies that have been so far treated with pharmacological approaches. We focused on the neuromodulation of autonomic nervous system activity with implantable devices, a field of BM that already demonstrated the ability to treat a variety of conditions, from inflammation to metabolic and cognitive disorders. So far our analysis focused on animal model such as rodents and pigs, to understand how we can decode metabolic conditions from autonomic nervous system activity, in particular in the carotid sinus nerve and the vagus nerve. Deep brain stimulation (DBS) is an effective therapy for pathological conditions including motor disorders. We addressed several open issues in DBS including accurate target localization, development of in silico tests for DBS, and identification of specific motor symptoms biomarkers. In particular, we were able to find markers of gait and impulse control disorders in the basal ganglia activity in parkinsonian patients. Analysis of kinematics from wearable sensors was used both to test the efficacy of the aforementioned therapies and of motor rehabilitation procedures. Finally, the potential of AI and deep learning have been investigated for the analysis of a wide range of medical images (endoscopy, ultrasound imaging, magnetic resonance imaging, RGB-D imaging) to support clinicians during the actual clinical and surgical procedures. Specifically, research activities included the development of advanced deep learning algorithms with particular attention to on-the-edge AI and distributed learning paradigms.

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36. Saponati M, Garcia-Ojalvo J, Cataldo E, Mazzoni A. Thalamocortical Spectral Transmission Relies on Balanced Input Strengths. Brain Topogr. 2022 Jan;35(1):4-18.
37. Cometa A, D'Orio P, Revay M, Micera S, Artoni F. Stimulus evoked causality estimation in stereo-EEG. J Neural Eng. 2021 Oct 4;18(5)
38. Dedola F, Ulloa Severino FP, Meneghetti N, Lemaire T, Cafarelli A, Ricotti L, Menciassi A, Cutrone A, Micera S, Mazzoni A Ultrasound stimulations induce prolonged depolarization and fast action potentials in leech neurons - IEEE Open Journal of Engineering in Medicine and Biology (2020) 1:23-32

Machine Learning-based industrial processes modelling, control, management and optimization

Principal investigator: Valentina Colla

Collaborators: Ismael Matino, Stefano Dettori, Silvia Cateni, Angelo Castellano, Vincenzo Iannino, Antonella Zaccara, Alice Petrucciani

Description

This research activity includes development of Machine-Learning based holistic models of industrial processes (e.g. focused on detailed forecasting of the main features of some energy and/or raw materials streams) to be included into optimization schemes and decision support systems supporting optimal resource management and reduction of environmental impact. AI-based optimization approaches are also included

Related publications

1. Dettori, S., Matino, I., Colla, V., Speets, R., A Deep Learning-based approach for forecasting off-gas production and consumption in the blast furnace, (2021) *Neural Computing and Applications*.
2. Matino I, Dettori, S., Catellano, A., Matino, R., Mocci, C., Vannocci, M., Maddaloni, A., Colla, V., Wolff, A., Machine Learning-Based Models for Supporting Optimal Exploitation of Process Off-Gases in Integrated Steelworks, (2021) *Advances in Intelligent Systems and Computing*, 1338. Springer, Cham, pp. 104-118.
3. Dettori, S., Matino, I., Colla, V., Speets, R., Deep Echo State Networks in Industrial Applications, (2020) *IFIP Advances in Information and Communication Technology*, 584 IFIP, pp. 53-63.
4. Vannucci, M., Colla, V., Dettori, S., Iannino, V., Fuzzy Adaptive Genetic Algorithm for Improving the Solution of Industrial Optimization Problems, (2020) *Journal of Intelligent Systems*, 29 (1), pp. 409-422.
5. Matino, I., Dettori, S., Colla, V., Weber, V., Salame, S., Forecasting blast furnace gas production and demand through echo state neural network-based models: Pave the way to off-gas optimized management, (2019) *Applied Energy*, 253, art. no. 113578.
6. Colla, V., Matino, I., Dettori, S., Cateni, S., Matino, R., Reservoir computing approaches applied to energy management in industry, (2019) *Communications in Computer and Information Science*, 1000, pp. 66-79.
7. Matino, I., Dettori, S., Colla, V., Weber, V., Salame, S., Two innovative modelling approaches in order to forecast consumption of blast furnace gas by hot blast stoves, (2019) Energy Procedia, 158, pp. 4043-4048.
8. Matino, I., Dettori, S., Colla, V., Weber, V., Salame, S., Application of Echo State Neural Networks to forecast blast furnace gas production: Pave the way to off-gas optimized management, (2019) *Energy Procedia*, 158, pp. 4037-4042.
9. Dettori, S., Matino, I., Colla, V., Weber, V., Salame, S., Neural network-based modeling methodologies for energy transformation equipment in integrated steelworks processes, (2019) *Energy Procedia*, 158, pp. 4061-4066.
10. Maddaloni, A., Matino, R., Matino, I., Dettori, S., Zaccara, A., Colla, V., A quadratic programming model for the optimization of off-gas networks in integrated steelworks, (2019) *Materiaux et Techniques*, 107 (5), art. no. 502.
11. Dettori, S., Iannino, V., Colla, V., Signorini, A., An adaptive Fuzzy logic-based approach to PID control of steam turbines in solar applications, (2018) *Applied Energy*, 227, pp. 655-664.
12. Nastasi, G., Colla, V., Cateni, S., Campigli, S., Implementation and comparison of algorithms for multi-objective optimization based on genetic algorithms applied to the management of an automated warehouse, (2018) *Journal of Intelligent Manufacturing*, 29 (7), pp. 1545-1557.

Machine Learning and Deep Learning for process control and product quality management in industrial applications

Principal investigator: Marco Vannucci

Collaborators: Valentina Colla, Antonio Ritacco, Claudio Mocci, Marco Vannocci, Silvia Cateni

Description

Design and development of Machine Learning and Deep Learning approaches for production processes control and product quality monitoring and management, including applications of Deep Learning to image processing for features extraction and defects detection and classification.

Related publications

1. J. Brandenburger, C. Schirm, J. Melcher, E. Hancke, M. Vannucci, V. Colla, S. Cateni, R. Sellami, S. Dupont, A. Majchrowski, A. Arteaga, Quality 4.0 - Transparent Product Quality Supervision in the Age of Industry 4.0, (2021) *Advances in Intelligent Systems and Computing*, 1338. Springer, Cham, pp. 54-66.
2. Galli, F., Ritacco, A., Lanciano, G., Vannocci, M., Colla, V., Vannucci, M., Self-supervised pre-training of CNNs for flatness defect classification in the steelworks industry, (2020) *International Journal of Advances in Intelligent Informatics*, 6 (1), pp. 13-22.
3. Vannucci, M., Colla, V., Quality improvement through the preventive detection of potentially defective products in the automotive industry by means of advanced artificial intelligence techniques, (2019) Smart Innovation, Systems and Technologies, 143, pp. 3-12.
4. Vannucci, M., Colla, V., Imbalanced datasets resampling through self organizing maps and genetic algorithms, (2019) *Communications in Computer and Information Science*, 1000, pp. 399-411.
5. Cateni, S., Colla, V., Vignali, A., Brandenburger, J., Cause and effect analysis in a real industrial context: Study of a particular application devoted to quality improvement, (2019) Smart Innovation, Systems and Technologies, 102, pp. 219-228.
6. Vannocci, M., Ritacco, A., Castellano, A., Galli, F., Vannucci, M., Iannino, V., Colla, V., Flatness Defect Detection and Classification in Hot Rolled Steel Strips Using Convolutional Neural Networks, (2019) *Lecture Notes in Computer Science*, 11507 LNCS, pp. 220-234.

AI-supported metallurgical science and technology

Principal investigator: Valentina Colla

Collaborators: Marco Vannucci, Silvia Cateni, Antonella Vignali, Claudio Mocci

Description

Development of ML-based hybrid models and approaches for forecasting of material properties targeted to their improvement through suitable design and control of production processes and operating practices.

Related publications

1. Vannucci M., Colla V., Ritacco A., Vannocci M., Vignali A. AI and ML Techniques for Generation and Assessment of Products Properties Data, (2021) *Advances in Intelligent Systems and Computing*, 1338. Springer, Cham, pp. 67-77.
2. Van Den Berg F., Fintelman D., Yang H., Mocci C., Vannucci M., Colla V., The Use of Advanced Data Analytics to Monitor Process-Induced Changes to the Microstructure and Mechanical Properties, (2021) *Advances in Intelligent Systems and Computing*, 1338. Springer, Cham, pp. 78-91.
3. Colla, V., Vannucci, M., Valentini, R. Prediction of the mechanical properties of rebars through a combination of finite element and data-driven models, (2020) *Metallurgia Italiana*, 112 (10), pp. 26-33.
4. Colla, V., Cateni, S., Maddaloni, A., Vignali, A., A modular machine-learning-based approach to improve tensile properties uniformity along hot dip galvanized steel strips for automotive applications, (2020) *Metals*, 10 (7), art. no. 923, pp. 1-23.
5. Colla, V., Vannucci, M., Bacchi, L., Valentini, R., Neural networks-based prediction of hardenability of high performance carburizing steels for automotive applications, (2020) *Metallurgia Italiana*, 112 (1), pp. 47-53.
6. Van Den Berg, F.D., Kok, P.J.J., Yang, H., Aarnts, M.P., Meilland, P., Kebe, T., Stolzenberg, M., Krix, D., Zhu, W., Peyton, A.J., Martinez-De-Guerenu, A., Gutierrez, I., Jorge-Badiola, D., Malmström, M., Volker, A., Duijster, A., Wirdelius, H., Boström, A., Mocci, C., Vannucci, M., Colla, V., Davis, C., Zhou, L., Schmidt, R., Labbé, S., Reboud, C., Skarlatos, A., Leconte, V., Lombard, P., Product uniformity control - A research collaboration of european steel industries to non-destructive evaluation of microstructure and mechanical properties, (2018) *Studies in Applied Electromagnetics and Mechanics*, 43, pp. 120-129.

AI-based Data Analytics and pre-processing for industrial data mining and knowledge extraction

Principal investigator: Marco Vannucci

Collaborators: Valentina Colla, Silvia Cateni, Antonella Vignali

Description

Design and development of algorithms for the analysis and pre-processing of industrial data. These algorithms are devoted to the dataset preparation and information extraction to further processing steps and include, among the others, features selection and outliers detection strategies.

Related publications

1. Cateni S., Colla V., Vignali A., Vannucci M. Data Pre-processing for Efficient Design of Machine Learning-Based Models to be Applied in the Steel Sector. (2021) *Advances in Intelligent Systems and Computing*, 1338. Springer, Cham, pp. 13-27.
2. Vannucci, M., Colla, V., Cateni, S., Genetic operators impact on genetic algorithms based variable selection, (2020) *Smart Innovation, Systems and Technologies*, 193, pp. 211-221.
3. Galli, F., Vannucci, M., Colla, V., Optimization of data resampling through GA for the classification of imbalanced datasets, (2019) *International Journal of Advances in Intelligent Informatics*, 5 (3), pp. 297-307.
4. Cateni, S., Colla, V., Iannino, V., Improving the stability of variable selection for industrial datasets, (2019) Smart Innovation, Systems and Technologies, 102, pp. 209-218.
5. Vannucci, M., Colla, V., Self-Organizing-Maps Based Undersampling for the Classification of Unbalanced Datasets, (2018) *Proc. International Joint Conference on Neural Networks*, 2018-July, art. no. 8489320.
6. Cateni, S., Ritacco, A., Iannino, V., Colla, V., Vannucci, M., Dettori, S., Smart data pre-processing modules and graphical user interfaces for machine learning tasks, (2018) *International Journal of Simulation: Systems, Science and Technology*, 19 (5), pp. 24.1-24.7.
7. Vannucci, M., Colla, V., Genetic algorithms based resampling for the classification of unbalanced datasets, (2018) *Smart Innovation, Systems and Technologies*, 73, pp. 23-32.

Multi-Agent Systems for industrial applications

Principal investigator: Vincenzo Iannino

Collaborators: Valentina Colla, Claudio Mocci

Description

Investigation and establishment of agent-based approaches for production simulation, optimization and high-level control of complex manufacturing processes. Design of a Multi-Agent System approach for modelling and self-optimizing a process chain enabling a smart manufacturing perspective. Implementation of an event-driven agent-based model for simulating and controlling the operations of a general industrial process to cope with production uncertainties. Implementation of industrial agents for the realization of cyber-physical systems devoted to the optimization of temperature profiles in factories producing long steel products. Development and implementation of a general framework and a software platform for the deployment and simulation of MAS in industrial applications

Related publications

1. Iannino V., Mocci C., Colla V. A Hybrid Peer-to-Peer Architecture for Agent-Based Steel Manufacturing Processes, (2021) Accepted for presentation at *17th IFAC Symposium on Information Control Problems in Manufacturing INCOM 2021*, 7-9 June 2021.
2. Iannino V., Mocci C., Colla V. A Brokering-Based Interaction Protocol for Dynamic Resource Allocation in Steel Production Processes. (2021) *Advances in Intelligent Systems and Computing*, vol 1368. Springer, Cham, pp 119-129.
3. Iannino, V., Mocci, C., Vannocci, M., Colla, V., Caputo, A., Ferraris, F., An event-driven agent-based simulation model for industrial processes, (2020) *Applied Sciences*, 10 (12), art. no. 4343.
4. Iannino, V., Colla, V., Denker, J., Göttsche, M., A CPS-based simulation platform for long production factories, (2019) *Metals*, 9 (10), art. no. 1025.
5. Iannino, V., Vannocci, M., Vannucci, M., Colla, V., Neuer, M., A multi-agent approach for the self-optimization of steel production, (2018) *International Journal of Simulation: Systems, Science and Technology*, 19 (5), pp. 20.1-20.7.
6. Marchiori, F., Benini, M., Cateni, S., Colla, V., Vignali, A., Ebel, A., Neuer, M.J., Piedimonte, L., Agent-based approach for energy demand-side management, (2018) *Stahl und Eisen*, 138 (2), pp. 25-29.

Robotic applications for the metallurgical sector

Principal investigator: Valentina Colla

Collaborators: Ruben Matino

Description

A full scale robotic workstation was developed and installed in a steel shop to support a particular maintenance procedure, the replacement of ladle refractory materials of the ladle sliding gate. Image processing was applied to guide robot operations through a dedicated vision tool. A Human-Machine Interface was also developed, to support operators in managing the robotic workstation. Further potential applications are under investigation.

Related publications

1. Colla, V., Matino, R., Schröder, A.J., Schivalocchi, M., Romaniello, L., Human-centered robotic development in the steel shop: Improving health, safety and digital skills at the workplace, (2021) *Metals*, 11 (4), art. no. 647.
2. Colla, V., Matino, R., Faes, A., Schivalocchi, M., Romaniello, L., Schröder, A., Usage of a robot to service slide gates of casting ladles, (2020) *Chernye Metally*, 2020 (3), pp. 4-8.
3. Colla, V., Matino, R., Faes, A., Schivalocchi, M., Romaniello, L., Schröder, A., Zoppirolli, A., A robot performs the maintenance of the ladle sliding gate, (2019) *Stahl und Eisen*, 139 (9), pp. 44-47.
4. Colla, V., Matino, R., Faes, A., Romaniello, L., Schröder, A., Robot-assisted replacement of the refractory components of the ladle sliding gate in a steel shop, (2019) *Proceedings of the 10th European Metallurgical Conference, EMC 2019*, 4, pp. 1441-1454.

Supporting wide deployment of AI and Big Data technologies in process industry

Principal investigator: Valentina Colla

Collaborators: Teresa Annunziata Branca, Barbara Fornai, Ismael Matino

Description

This research lines aims at favoring the full exploitation of the potential of AI and Big Data technologies and their full deployment in process industry to preserve technological leadership, improve competitiveness and socio-economic and environmental sustainability of production processes. It includes also the topic of vocational training and personnel upskilling through targeted training measures and development of blueprint for professional education, which is deepened through the participation to EU-funded dissemination projects as well as two Erasmus Plus projects.

Related publications

1. Colla, V., Pietrosanti, C., Malfa, E., Peters, K., Environment 4.0: How digitalization and machine learning can improve the environmental footprint of the steel production processes, (2020) *Materiaux et Techniques*, 108 (5-6), art. no. 2021007.
2. Branca, T.A., Fornai, B., Colla, V., Murri, M.M., Streppa, E., Schroder, A.J., Current and future aspects of the digital transformation in the European Steel Industry, (2020) *Materiaux et Techniques*, 108 (5-6), art. no. 2021010.
3. Branca, T.A., Fornai, B., Colla, V., Murri, M.M., Streppa, E., Schröder, A.J., The challenge of digitalization in the steel sector, (2020) *Metals*, 10 (2), art. no. 288.
4. Matino, I., Branca, T.A., Fornai, B., Colla, V., Romaniello, L., Scenario Analyses for By-Products Reuse in Integrated Steelmaking Plants by Combining Process Modeling, Simulation, and Optimization Techniques, (2019) *Steel Research International*, 90 (10), art. no. 1900150, .
5. Matino, I., Colla, V., Baragiola, S., Internal Slags Reuse in an Electric Steelmaking Route and Process Sustainability: Simulation of Different Scenarios Through the EIRES Monitoring Tool, (2018) *Waste and Biomass Valorization*, 9 (12), pp. 2481-2491.

AI for industrial quality inspection

Principal investigator: Paolo Tripicchio

Collaborators: Salvatore D'Avella, Paolo Sassi, Gerardo Camacho, Carlo Alberto Avizzano

Description

This research activity is focused on the application of AI methodologies for the development of novel approaches and systems able to monitor and inspect the quality of products on industrial production lines. The fundamental research question is how to integrate modern AI architecture in the industrial sector sustaining the industrial KPIs without increasing system usage complexity.
The inspection can be performed with static platform as well as with mobile dynamic platforms provided with localization capabilities and human like reasoning to behave similarly to humans.

Related publications

1. D'Avella, S., Camacho-Gonzalez, G., Tripicchio, P. , On Multi-Agent Cognitive Cooperation: Can virtual agents behave like humans?, Neurocomputing 480 (2022), pp. 27-38
2. D'avella, S., Unetti, M., Tripicchio, P., RFID Gazebo based simulator with RSSI and Phase signals for UHF tags localization and tracking., IEEE Access (2022)
3. Bernardini, F., Motroni, A., Nepa, P., (...), Buffi, A., Del Col, L., The MONITOR project: RFID-based robots enabling real-time inventory and localization in warehouses and retail areas, 2021 6th International Conference on Smart and Sustainable Technologies, SpliTech 2021
4. Baris, G., Avizzano, C.A., Accurate Identification of 3D Pose through Reprojection onto a Single Image from Mask-RCNN Contour, IEEE Symposium on Emerging Technologies and Factory Automation, ETFA 2020-September, pp. 1487-1494
5. Sassi, Paolo, Paolo Tripicchio, and Carlo Alberto Avizzano. "A smart monitoring system for automatic welding defect detection." *IEEE Transactions on Industrial Electronics* 66.12 (2019): 9641-9650.
6. Tripicchio, Paolo, Gerardo Camacho-Gonzalez, and Salvatore D'Avella. "Welding defect detection: coping with artifacts in the production line." *The International Journal of Advanced Manufacturing Technology* 111.5 (2020): 1659-1669.

Vision Based flexible robotic manipulation for industry

Principal investigator: Paolo Tripicchio

Collaborators: Salvatore D'Avella, Alessandro Filippeschi, Carlo Alberto Avizzano, Matteo Tanzini,

Description

This activity deals with the application of modern AI driven computer vision tools to manipulate flexible or deformable object through robotic tools. AI provides a solid object detection and classification framework that integrates with computer vision and motion planning in robot.
In the related works we performed application studies to three different sectors: automotive components, Industrial manipulation and construction

Related publications

1. D'Avella, Salvatore, Paolo Tripicchio, and Carlo Alberto Avizzano. "A study on picking objects in cluttered environments: Exploiting depth features for a custom low-cost universal jamming gripper." *Robotics and Computer-Integrated Manufacturing* 63 (2020).
2. Tripicchio, P., D'Avella, S., Is deep learning ready to satisfy industry needs?, Procedia Manufacturing (2020) 51, pp. 1192-1199
3. D'Avella, S., Tripicchio, P., Supervised stowing as enabling technology for the integration of impaired operators in the industry, Procedia Manufacturing (2020) 51, pp. 171-178
4. D'Avella, Salvatore, and Paolo Tripicchio. "Supervised stowing as enabling technology for the integration of impaired operators in the industry." *Procedia Manufacturing* 51 (2020): 171-178.
5. Tripicchio, Paolo, Carlo Alberto Avizzano, and Massimo Bergamasco. "A 6-DOF haptic manipulation system to verify assembly procedures on CAD models." *Procedia Manufacturing* 38 (2019): 1292-1299.
6. Tanzini, Matteo, et al. "Embedded Architecture of a Hydraulic Demolition Machine for Robotic Teleoperation in the Construction Sector." *2018 IEEE 14th International Conference on Automation Science and Engineering (CASE)*. IEEE, 2018.

Robotics and AI augmented human assistance and surveillance for health and safety

Principal investigator: Alessandro Filippeschi & Carlo Alberto Avizzano

Collaborators: Paolo Tripicchio, Giulia Bassani, Paolo Giannini, Emanuele Ruffaldi, Lorenzo Landolfi, Juan Manuel Jacinto Villegas

Description

AI is being employed in different contexts to help and interact with users: as a means to survey regularity of operation; as a means to detect health issues during work activities; and as a tool to relate biometric signals to health risks. The technologies are being applied in several contexts such as: workplace surveillance, monitoring of work operation, assistance to impaired and elderly people, telemedicine, and sport.

Related publications

1. G. Bassani, A. Filippeschi, E. Ruffaldi, “Nonresonant kinetic energy harvesting using macrofiber composite patch”, *IEEE Sensors Journal,* 18 (5), pp. 2068-2076, 2018
2. A. Filippeschi, F. Brizzi, E. Ruffaldi, J.M. Jacinto Villegas, L. Landolfi, C.A. Avizzano, “Evaluation of diagnostician user interface aspects in a virtual reality-based teleultrasonography simulation”, *Advanced Robotics*, 33, 15-16, pp. 840-852, Taylor & Francis, 2019
3. Tripicchio, P., D’avella, S., Ruffaldi, E., Real-Time Numerical Simulation for Accurate Soft Tissues Modeling during Haptic Interaction, Actuators (2022) 11(1),17
4. Avizzano, Carlo Alberto, et al. "Real-Time Embedded Vision System for the Watchfulness Analysis of Train Drivers." *IEEE Transactions on Intelligent Transportation Systems*, 2019.
5. Giannini, Paolo, et al. "Wearable sensor network for biomechanical overload assessment in manual material handling." *Sensors* 20.14, pp. 3877, 2020
6. Capellini, K., Tripicchio, P., Vignali, E., (...), Tanca, C., Celi, S., 3D printing and 3D virtual models for surgical and percutaneous planning of congenital heart diseases, VISIGRAPP 2020 - Proceedings of the 15th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications 3, pp. 281-287
7. A. Filippeschi, P. Griffa, C.A. Avizzano, “Kinematic Optimization for the Design of a Collaborative Robot End-Effector for Tele-Echography”, *Robotics,* 10 (1), 8, MDPI, 2021
8. Filippeschi, Alessandro, et al. "Towards Skills Evaluation of Elderly for Human-Robot Interaction." *2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*. IEEE, 2018.
9. Filippeschi, Alessandro, et al. "Online Calibration Procedure for Motion Tracking with Wearable Sensors Using Kalman Filtering." *International Symposium on Advances in Robot Kinematics*. Springer, Cham, 2018.
10. J.M. Jacinto Villegas, A. Filippeschi, C.A. Avizzano, E. Ruffaldi, “Preliminary Stiffness Perception Assessment for a Tele-palpation Haptic Interface”, *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*, pp. 175-185, Springer, Cham, 2018
11. A. Filippeschi, J.M. Jacinto Villegas, M. Satler, C.A.Avizzano, “A novel diagnostician hptic interface for tele-palpation”, *2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*. IEEE, 2018
12. Filippeschi, Alessandro, et al. "The Sailport Project: A Trilateral Approach to the Improvement of Workers' Safety and Health in Ports." *International Conference on Applied Human Factors and Ergonomics*. Springer, Cham, 2019.
13. Landolfi, Lorenzo, et al. "Fast and Fluid Human Pose Tracking." *2019 IEEE International Conference on Real-time Computing and Robotics (RCAR)*. IEEE, 2019.
14. P. Griffa, A. Filipeschi, C.A.Avizzano, “Kinematic Optimization for the Design of a UR5 Robot End-Effector for Cardiac Tele-Ultrasonography”, *The International Conference of IFToMM ITALY*, Springer, Cham, 2020

Driverless and Autonomous mobile systems

Principal investigator: Satler Massimo & Carlo Alberto Avizzano

Collaborators: Edwin Herrera, Davide Bagheri, Dinojan Pedurupillai, Antonio Frisoli, Luca Tiseni, Michele Tonutti, Domenico Chiaradia, Paolo Tripicchio

Description

Several driverless autonomous mobile system projects have been started within the context of the department of Excellence in Robotics and Automation. Together with Leonardo SpA we are running the Leonardo Drone contest, a three years multi-academic program to leverage the industrial knowledge in indoor drone driving operation. In cooperation with university of Pisa we promote student research and undergraduate activities in usage of AI for driverless racing cars. In cooperation with transportation and automotive companies we develop tools, robot and software that exploit AI for autonomous navigation and detection of anomalies.

Related publications

1. Alarcon, E.P.H., Ghavifekr, D.B., Baris, G., (...), Satler, M., Avizzano, C.A., An Efficient Object-Oriented Exploration Algorithm for Unmanned Aerial Vehicles, 2021 International Conference on Unmanned Aircraft Systems, ICUAS 2021, pp. 330-337
2. Tonutti, Michele, et al. "Robust and subject-independent driving manoeuvre anticipation through Domain-Adversarial Recurrent Neural Networks." *Robotics and Autonomous Systems* 115 (2019): 162-173.
3. Tripicchio, P., D'Avella, S., Modeling multiple vehicle interaction constraints for behavior prediction of vehicles on highways, Computers and Electrical Engineering (2022) 98
4. Tripicchio, Paolo, et al. "Confined spaces industrial inspection with micro aerial vehicles and laser range finder localization." *International Journal of Micro Air Vehicles* 10.2 (2018): 207-224.
5. Chiaradia, Domenico, et al. "A Mobile Robot for Undercarriage Inspection on Standard Railway Tracks." *The International Conference of IFToMM ITALY*. Springer, Cham, 2020.
6. Tiseni, Luca, et al. "UV-C Mobile Robots with Optimized Path Planning: Algorithm Design and On-Field Measurements to Improve Surface Disinfection Against SARS-CoV-2." *IEEE Robotics & Automation Magazine* 28.1 (2021): 59-70.

Smart mobile localization and tracking

Principal investigator: Paolo Tripicchio

Collaborators: Salvatore D'Avella, Matteo Unetti

Description

This research activity is focused on the integration of wireless sensing with classical laser and camera based localization techniques to improve industrial logistics and retail applications with AI methods.

Related publications

1. Tripicchio, Paolo, et al. "A Synthetic Aperture UHF RFID Localization Method by Phase Unwrapping and Hyperbolic Intersection." *IEEE Transactions on Automation Science and Engineering* (2021).
2. Bernardini, F. et al. "Particle Swarm Optimization in SAR-Based Method Enabling Real-Time 3D Positioning of UHF-RFID Tags." *IEEE Journal of Radio Frequency Identification* (2020).
3. Motroni, Andrea, et al. "Towards a multi-antenna approach for UHF-RFID tag 3D localization with a synthetic aperture radar method." *2019 4th International Conference on Smart and Sustainable Technologies (SpliTech)*. IEEE, 2019.
4. Motroni, Andrea, et al. "A multi-antenna SAR-based method for UHF RFID tag localization via UGV." *2018 IEEE International Conference on RFID Technology & Application (RFID-TA)*. IEEE, 2018.
5. Bernardini, F., et al. "Particle swarm optimization in multi-antenna SAR-based localization for UHF-RFID tags." *2019 IEEE International Conference on RFID Technology and Applications (RFID-TA)*. IEEE, 2019.

Industrial Maintenance and Maintenance on Condition

Principal investigator: Carlo Alberto Avizzano & Antonio Frisoli

Collaborators: Massimiliano Solazzi, Gabriele Baris, Federica Fioretti, Emanuele Ruffaldi

Description

Product and good quality should be monitored at production and during the whole lifetime of goods usage. This is of particular importance for transportation and automotive field where the safety of passengers is depending on the level of maintenance of the vehicle. Within this context the PERCRO laboratory has actively cooperated with some major Italian players in the fields, among these: Trenitalia, RFI, Magneti Marelli and Continental. The goal of such collaboration is to produce AI helped system that constantly monitor products and systems to validate from images and 3D vision that the product or the system is conforming to the operational standards.

Related publications

1. Baris, Gabriele, and Carlo Alberto Avizzano. "Accurate Identification of 3D Pose through Reprojection onto a Single Image from Mask-RCNN Contour." *2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*. Vol. 1. IEEE, 2020.
2. Fioretti, Federica, Emanuele Ruffaldi, and Carlo Alberto Avizzano. "A single camera inspection system to detect and localize obstacles on railways based on manifold Kalman filtering." *2018 IEEE 23rd International Conference on Emerging Technologies and Factory Automation (ETFA)*. Vol. 1. IEEE, 2018.

Design of path-planning algorithms for robotic disinfection

Principal investigator: Antonio Frisoli

Collaborators: Daniele Leonardis, Luca Tiseni, Massimiliano Solazzi, Massimiliano Gabardi, Domenico Chiaradia

Description

Ultraviolet type-C irradiation (UV-C) is an effective no-contact disinfection procedure for surfaces and environments to reduce the spread of severe acute respiratory syndrome corona virus 2 (SARS-CoV-2), the virus that causes COVID-19. This work evaluates the effect of the adoption of mobile robots for UV-C irradiation, compared to conventional disinfection methods based on static UV-C lamps. A novel trajectory planner has been developed. It consists of a genetic algorithm (GA) that explores the possible trajectories and disinfection outcomes of a robot moving in a tunable artificial potential field (APF) and is capable of maximizing the delivered UV dose based on ambient geometry. The experimental results show that, compared to a conventional trajectory, an optimized one has better performance in terms of both the coverage of the radiated energy in the environment and the time required to complete the disinfection task.

Related publications:

1. L. Tiseni, D. Chiaradia, M. Gabardi, M. Solazzi, D. Leonardis and A. Frisoli, "UV-C Mobile Robots with Optimized Path Planning: Algorithm Design and On-Field Measurements to Improve Surface Disinfection Against SARS-CoV-2," in *IEEE Robotics & Automation Magazine*, vol. 28, no. 1, pp. 59-70, March 2021, doi: 10.1109/MRA.2020.3045069.

1. AI techniques for intuitive control of exoskeleton based on motion intention detection and muscle synergies extraction

Principal investigator: Antonio Frisoli

Collaborators: Cristian Camardella

Description

Pilot training data of a patient with recurrent acute ischemia were collected during training sessions, in a context of robot-aided upper limb rehabilitation. Tasks required the subject to move a car in a 2D serious game using a planar manipulandum (horizontal plane), along pre-defined trajectories. Seventeen training sessions, spanned on three weeks, were accomplished, each containing: kinematic and upper limb forces data, well as a high number of other session variables like the total work of the robot, range of motion estimation, average of robot activity time (not Automode), total performed distance and session duration. From all these variables, a feature selection process is needed before addressing the prediction step. An investigation on the most popular or recent methods in literature, for the aforementioned purpose, led to five potential solutions: random forest, autoencoders, principal component analysis, linear discriminant analysis and artificial neural networks. In particular, random forest and autoencoders are potential solutions in overcoming limitations of methods based on statistical inference. A preliminary complete features set has been selected, including: forces features (directions with amounts over threshold, mean, standard deviation), size of workspace covered area, total time of robot Automode, total work of subject, session duration, total distance, and robot speed (average and standard deviation). A comparison of features selection methods will be performed, mainly basing on the outcomes of different regression algorithms that will exploit the selected features set. Multivariate linear regression or kernel ridge regression are potential solutions in the prediction phase, that is linking the variation of features values to variations of clinical scale scores, that will be available at pre-assessment and discharge timings.

Related publications

1 Camardella, C., Porcini, F., Filippeschi, A., Marcheschi, S., Solazzi, M., Frisoli, A. “Gait Phases Blended Control for Enhancing Transparency on Lower-Limb Exoskeletons” (2021) IEEE Robotics and Automation Letters, 6 (3), art. no. 9415159, pp. 5453-5460.

2 Camardella, Cristian, et al. "Investigating muscle synergies changes after rehabilitation robotics training on stroke survivors: a pilot study." 2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC). IEEE, 2020.

3 Camardella, C., Barsotti, M., Buongiorno, D., Frisoli, A., & Bevilacqua, V. (2020). Towards online myoelectric control based on muscle synergies-to-force mapping for robotic applications. Neurocomputing.

4 Buongiorno, D., Cascarano, G. D., Camardella, C., De Feudis, I., Frisoli, A., & Bevilacqua, V. (2020). Task-Oriented Muscle Synergy Extraction Using An Autoencoder-Based Neural Model. Information, 11(4), 219 Information.

Ethorobotics as a novel translational neuroethological engineering approach to turn findings into outcomes within real-world healthcare contexts

Principal investigator: Cesare Stefanini, Donato Romano

Collaborators: Michael Tannous

Description

We propose ethorobotics (e.g. an emerging field of bioengineering that brings bionics at an higher level of biological organization) to establishing biohybrid communities between animals and robots, to recognize novel network interactions on the mental, physical and biochemical level that can be exploited for appropriate therapies during preclinical stages. It has been proposed an increasing role played by the cognitive control mechanisms as a compensation strategy for age-related sensorimotor reduction, and many evidences show that older brains exhibit better adaptive benefits related to previous motor experiences compared to younger ones. We carried out pilot studies by developing biomimetic robotic predators to evoke anti-predator motor responses in locusts (valuable biological models, due to some basic organization principles of their brain that are similar to higher vertebrates) whose results can be exploited to ameliorate motor decline in older adults.
Furthermore, we used biomimetic robots to interact with social fish to further understand the mechanisms and the evolution of social distancing. Social distancing, based on the reduction of contact rates among individuals through behavioural changes, is an important aspect in reducing the transmission of a large number of diseases in humans. Our study prompts more attention on the role of behavioural-based strategies to avoid pathogen/parasite diffusion, and can be used to optimize computational approaches to model disease dynamics.
In addition, we used social fish species to interact with life-like robotic agents to understand intrinsic and extrinsic mechanisms causing anxiety, and how social robots can be effectively used as anxiety treatments.

Related publications

1. Romano, D., Stefanini, C. Robot-fish interaction helps to trigger social buffering in neon tetras: the potential role of social robotics in treating anxiety. International Journal of Social Robotics. https://doi.org/10.1007/s12369-021-00829-y
2. Romano, D., & Stefanini, C. (2021). Unveiling social distancing mechanisms via a fish-robot hybrid interaction. Biological Cybernetics, 1-9. https://doi.org/10.1007/s00422-021-00867-9
3. Romano, D., Bloemberg, J., Tannous, M., & Stefanini, C. (2020). Impact of aging and cognitive mechanisms on high-speed motor activation patterns: evidence from an orthoptera-robot interaction. IEEE Transactions on Medical Robotics and Bionics, 2(2), 292-296.

Animal-robot interaction paradigm to face engineering and environmental challenges through sustainable strategies

Principal investigator: Cesare Stefanini, Donato Romano

Collaborators: -

Description

We propose a paradigm shift at the interface of ethology and robotics based on biohybrid intelligent systems with many potential applications in different areas including ecological monitoring and manipulation, agriculture, engineering, A.I., bionics, and more. In animal-robot interaction contexts, biomimetic agents are perceived as natural heterospecifics or conspecifics by animals, creating biohybrid dynamic systems where robots detect, communicate and interact with the animals, triggering in the latter, specific neuro-behavioural responses, and adapting their behaviour according with the animal's one. Beside new knowledge, animal-robot interactive systems can produce a notable socio-economic impact on our daily lives, as well as on the influences of humans on the environment.
The use of interactive artificial agents to study animal intelligence relies on multiple disciplines, such as biomimetics, robotics, machine learning, biosystems engineering, neuroethology. etc. Animals are elective model organisms to develop new methods in the fields mentioned above, thanks to their ability in learning and remembering, their inter-individual differences, their adaptation to environmental perturbations. These abilities can be used to face primary challenges in robotics, especially when artificial agents are in the real world interacting with biotic and abiotic factors (including interactions with humans). This scientific field has several crucial aims including animal wellness improvements and environmental sustainability through mitigation of human activities on ecosystems. From an engineering point of view, animal-robot interaction can allow the creation of distributed hybrid networks of sensors and actuators composed of animals and robots, bringing new emerging cognitive and physical capabilities to current bioinspired robotic systems.

Related publications

1. Romano, D., Stefanini, C. (2021, April). Any colour you like: using animal-robot interaction to unravel mechanisms promoting phenotypically heterogeneous fish aggregations. In ALIFE 2021: The 2021 Conference on Artificial Life. MIT Press.
2. Stefanini, C., Romano, D. (2021, April). Towards animal phenotype transfer into biomimetic robots: the LAMPETRA project. In ALIFE 2021: The 2021 Conference on Artificial Life. MIT Press.
3. Romano, D., & Stefanini, C. (2021). Individual neon tetras (Paracheirodon innesi, Myers) optimise their position in the group depending on external selective contexts: Lesson learned from a fish-robot hybrid school. Biosystems Engineering, 204, 170-180.
4. Romano, D., Benelli, G., & Stefanini, C. (2021). Opposite valence social information provided by bio-robotic demonstrators shapes selection processes in the green bottle fly. Journal of the Royal Society Interface, 18(176), 20210056.
5. Romano, D., & Stefanini, C. (2021). Bio-robotic cues show how the Trinidadian guppy male recognises the morphological features of receptive females. Behavioural Processes, 182, 104283.
6. Romano, D., Benelli, G., Kavallieratos, N. G., Athanassiou, C. G., Canale, A., & Stefanini, C. (2020). Beetle-robot hybrid interaction: sex, lateralization and mating experience modulate behavioural responses to robotic cues in the larger grain borer *Prostephanus truncatus* (Horn). Biological Cybernetics, 114(4), 473-483.
7. Romano, D., Elayan, H., Benelli, G., & Stefanini, C. (2020). Together We Stand–Analyzing Schooling Behavior in Naive Newborn Guppies through Biorobotic Predators. Journal of Bionic Engineering, 17(1), 174-184.

Natural intelligence for bioinspired computing and eco-friendly ecosystem management methods

Principal investigator: Cesare Stefanini, Donato Romano

Collaborators: -

Description

We carried out several research activities that lead to important discoveries of great interest for integrated pest management (IPM) programs, and to understand animal intelligence that can inspire new life-like metaheuristic approaches in engineering contexts. Particularly, numerous studies focused on lateralization and reproductive behaviours in several insects species that are used as natural enemies in biological pest control, as well as pest insect species.
We reported crucial evidences that can be exploited to better understand the behavioural ecology of these species, and thus to develop more reliable models of their populations dynamic.
These findings are of great importance to improve techniques used in ecological engineering.

Related publications

1. Boukouvala, M. C., Romano, D., Kavallieratos, N. G., Stefanini, C., Canale, A., & Benelli, G. (2021). Behavioral Asymmetries Affecting Male Mating Success in *Tenebrio molitor* (Coleoptera: Tenebrionidae), an Important Edible Species. Journal of Economic Entomology. https://doi.org/10.1093/jee/toaa285
2. Benelli, G., Ricciardi, R., Romano, D., Cosci, F., Stefanini, C., & Lucchi, A. (2020). Wing-fanning frequency as a releaser boosting male mating success—High-speed video analysis of courtship behavior in *Campoplex capitator*, a parasitoid of *Lobesia botrana*. Insect Science, 27(6), 1298-1310.
3. Boukouvala, M. C., Romano, D., Kavallieratos, N. G., Athanassiou, C. G., Stefanini, C., Conte, G., ... & Benelli, G. (2020). Does geographical origin affect lateralization and male mating success in *Rhyzoperha dominica* beetles?. Journal of Stored Products Research, 88, 101630.
4. Sakka, M. K., Romano, D., Stefanini, C., Canale, A., Benelli, G., & Athanassiou, C. G. (2020). Mobility parameters of *Tribolium castaneum* and *Rhyzopertha dominica* populations with different susceptibility to phosphine. Journal of Stored Products Research, 87, 101593.

Novel Human-centered control approaches in Industry 4.0 context: special focus on welding process

Principal investigator: Cesare Stefanini

Collaborators: Michael Tannous, Marco Miraglia, Abanti Afroz, Francesca Digiacomo, Francesco Bologna, Francesco Inglese, Mario Milazzo

Description

We achieved several interesting results in the Industry 4.0 context with a special focus on the welding process. Research core is based on a human-centered design approach to improve quality and flexibility in such a complex and variable process. For instance, a head-mounted real-time tracking system for welding pool detection is developed to improve quality control in manual welding using advanced image processing algorithms. In a robot welding scenario instead, an innovative path-planning generated from workpiece design is proposed for quality control process. As for robot welding in collaborative context, a haptic based touch detection is proposed as a tactile feedback for the operator during a remote welding operation to improve seam quality.
Furthermore, a fruitful joint-lab activity with our industrial partner supported the design, development and testing activities in a real use case scenario leading to robust design and valuable experimental results.

Related publications

1. Afroz, A. S., Inglese, F., Stefanini, C., & Milazzo M. (2021). STL_Process: A STL-based preprocessor for robot path planning in manufacturing and quality control processes. SoftwareX. In Press
2. Afroz, A. S., Digiacomo, F., Pelliccia, R., Inglese, F., Stefanini, C., & Milazzo, M. (2020). Optimization of a wearable speed monitoring device for welding applications. The International Journal of Advanced Manufacturing Technology, 110(5), 1285-1293.
3. Digiacomo, F., Afroz, A. S., Pelliccia, R., Inglese, F., Milazzo, M., & Stefanini, C. (2020). Head-mounted standalone real-time tracking system for moving light-emitting targets fusing vision and inertial sensors. IEEE Transactions on Instrumentation and Measurement, 69(11), 8953-8961.
4. Tannous, M., Miraglia, M., Inglese, F., Giorgini, L., Ricciardi, F., Pelliccia, R., ... & Stefanini, C. (2020). Haptic-based touch detection for collaborative robots in welding applications. Robotics and Computer-Integrated Manufacturing, 64, 101952.
5. Tannous, M., Bologna, F., & Stefanini, C. (2020). Load cell torques and force data collection during tele-operated robotic gas tungsten arc welding in presence of collisions. Data in brief, 31, 105981.

AI and data science strategies for tactile sensing and augmenting haptic feedback with applications to bionic prostheses, healthcare technologies, collaborative robotics and industry 4.0

Principal investigator: Calogero Maria Oddo

Collaborators: *Intra department*. Federico Bianchi, Renato Caliò, Domenico Camboni, Maria Chiara Carrozza, Ilaria Cesini, Gastone Ciuti, Simona Crea, Tamas Czimmermann, Jessica D'Abbraccio, Giacomo D'Alesio, Paolo Dario, Giuseppe de Alteriis, Davide Ferraro, Mariangela Filosa, Giulia Fransvea, Clara Genna, Luca Massari, Alberto Mazzoni, Arianna Menciassi, Silvestro Micera, Mario Milazzo, Sara Moccia, Sahana Prasanna, Stefano Roccella, Udaya Bhaskar Rongala, Angelo Maria Sabatini, Francesca Sorgini, Giacomo Spigler, Giuseppe Terruso, Nicola Vitiello. *Intra university*. Alberto Di Minin, Michele Emdin, Alberto Giannoni, Vincenzo Lionetti, Claudio Passino. *External*. Massimo Barbaro, Lorenzo Capineri, Kalind Carpenter, Carmelo Chisari, Henrik Jörntell, Luca Fanucci, Eugenio Guglielmelli, Carlo Massaroni, Francesco Moscato, Eduardo Palermo, Gianni Pedrizzetti, Petar Petrovic, Luigi Raffo, Paolo Maria Rossini, Paola Saccomandi, Emiliano Schena, Edoardo Sinibaldi, Loredana Zollo.

Description

This research strand aimed at developing artificial intelligence and data science solutions to elaborate information generated by tactile sensors and to control wearable interfaces for augmenting haptic feedback. The applications targeted by such key enabling technologies were in a variety of scenarios, ranging from bionic prostheses and healthcare technologies up to collaborative robotics and industry 4.0.
To this aim, neuroscientific studies were undertaken with electrophysiological techniques such as patch clamp, microneurography, microneurostimulation and electroencephalography, to investigate the neurophysiological processes underlying natural intelligence and body-brain relationships with specific reference to the tactile sensory system. This set of fundamental knowledge was then translated to the development of sensors and human-machine interfaces. Specific breakthroughs included the demonstration of the feasibility to elicit rich tactile sensory perception through neural interfaces for bionic upper limb prostheses, the delivery of augmenting haptic sensory feedback for lower limb prostheses and telepresence, sensors and AI strategies for heart activity biomechanical monitoring, sensorized capsules and machine learning for colonoscopy, biomechatronic platforms for histological analyses through artificial palpation and multisensory integration, sensors for collaborative robotics applied to assistive technologies and industry 4.0.

Related publications

Applications to bionic prostheses

1. Vecchio, F., Miraglia, F., Alù, F., Valle, G., Mazzoni, A., Oddo, C. M., Micera, S. & Rossini, P. M. (2021). Brain network modulation in transradial amputee with finger perception restored through biomimetic intraneural stimulation. *Neurological Sciences*, 1-4.
2. Ferraro, D., D'Alesio, G., Camboni, D., Zinno, C., Costi, L., Haberbusch, M., ... & Oddo, C. M. (2021). Implantable Fiber Bragg Grating sensor for continuous heart activity monitoring: ex-vivo and in-vivo validation. *IEEE Sensors Journal*.
3. Cesini, I., Martini, E., Filosa, M., Spigler, G., Sabatini, A. M., Vitiello, N., Oddo, C. M. & Crea, S. (2020). Perception of time-discrete haptic feedback on the waist is invariant with gait events. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *28*(7), 1595-1604.
4. de Alteriis, G., & Oddo, C. M. (2021, May). Tradeoff between accuracy and computational cost of Euler and Runge Kutta ODE solvers for the Izhikevich spiking neuron model. In *2021 10th International IEEE/EMBS Conference on Neural Engineering (NER)* (pp. 730-733). IEEE.
5. Rongala, U. B., Mazzoni, A., Spanne, A., Jörntell, H., & Oddo, C. M. (2020). Cuneate spiking neural network learning to classify naturalistic texture stimuli under varying sensing conditions. *Neural Networks*, *123*, 273-287.

6. Mazzoni, A., Oddo, C. M., Valle, G., Camboni, D., Strauss, I., Barbaro, M., ... & Micera, S. (2020). Morphological neural computation restores discrimination of naturalistic textures in trans-radial amputees. *Scientific reports*, *10*(1), 1-14.
7. Martini, E., Cesini, I., D'Abbraccio, J., Arnetoli, G., Doronzio, S., Giffone, A., Meoni, B., Oddo, C. M., Vitiello, N. & Crea, S. (2020). Increased Symmetry of Lower-Limb Amputees Walking With Concurrent Bilateral Vibrotactile Feedback. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *29*, 74-84.
8. Cesini, I., Spigler, G., Prasanna, S., D'abbraccio, J., De Luca, D., Dell'Agnello, F., ... & Oddo, C. M. (2020). Assessment of intuitiveness and comfort of wearable haptic feedback strategies for assisting level and stair walking. *Electronics*, *9*(10), 1676.
9. Gunasekaran, H., Spigler, G., Mazzoni, A., Cataldo, E., & Oddo, C. M. (2019). Convergence of regular spiking and intrinsically bursting Izhikevich neuron models as a function of discretization time with Euler method. *Neurocomputing*, *350*, 237-247.
10. Rongala, U. B., Mazzoni, A., Chiurazzi, M., Camboni, D., Milazzo, M., Massari, L., ... & Oddo, C. M. (2019). Tactile decoding of edge orientation with artificial cuneate neurons in dynamic conditions. *Frontiers in neurorobotics*, *13*, 44.
11. Esposito, D., Lanotte, F., Mugnai, C., Massari, L., Camboni, D., Mazzoni, A., & Oddo, C. M. (2019). A neuromorphic model to match the spiking activity of Merkel mechanoreceptors with biomimetic tactile sensors for bioengineering applications. *IEEE Transactions on Medical Robotics and Bionics*, *1*(2), 97-105.
12. Enander, J., Spanne, A., Mazzoni, A., Bengtsson, F., Oddo, C. M., & Jörntell, H. (2019). Ubiquitous neocortical decoding of tactile input patterns. *Frontiers in cellular neuroscience*, *13*, 140.
13. Romeo, R. A., Rongala, U. B., Mazzoni, A., Camboni, D., Carrozza, M. C., Guglielmelli, E., ... & Oddo, C. M. (2018). Identification of slippage on naturalistic surfaces via wavelet transform of tactile signals. *IEEE Sensors Journal*, *19*(4), 1260-1268.
14. Genna, C., Oddo, C. M., Fanciullacci, C., Chisari, C., Micera, S., & Artoni, F. (2018). Bilateral cortical representation of tactile roughness. Brain research, 1699, 79-88.
15. Rongala, U. B., Spanne, A., Mazzoni, A., Bengtsson, F., Oddo, C. M., & Jörntell, H. (2018). Intracellular dynamics in cuneate nucleus neurons support self-stabilizing learning of generalizable tactile representations. *Frontiers in cellular neuroscience*, *12*, 210.
16. Sorgini, F., Caliò, R., Carrozza, M. C., & Oddo, C. M. (2018). Haptic-assistive technologies for audition and vision sensory disabilities. *Disability and Rehabilitation: Assistive Technology*, *13*(4), 394-421.
17. Genna, C., Oddo, C. M., Mazzoni, A., Wahlbom, A., Micera, S., & Jörntell, H. (2018). Bilateral tactile input patterns decoded at comparable levels but different time scales in neocortical neurons. *Journal of Neuroscience*, *38*(15), 3669-3679.
18. Cesini, I., Spigler, G., Prasanna, S., Taxis, D., Dell'Agnello, F., Martini, E., ... & Oddo, C. M. (2018, October). A wearable haptic feedback system for assisting lower-limb amputees in multiple locomotion tasks. In *International Symposium on Wearable Robotics* (pp. 115-119). Springer, Cham.
19. Filosa, M., Cesini, I., Martini, E., Spigler, G., Vitiello, N., Oddo, C., & Crea, S. (2018, October). A new sensory feedback system for lower-limb amputees: Assessment of discrete vibrotactile stimuli perception during walking. In *International Symposium on Wearable Robotics* (pp. 105-109). Springer, Cham.
20. Rongala, U. B., Mazzoni, A., Camboni, D., Carrozza, M. C., & Oddo, C. M. (2018). Neuromorphic artificial sense of touch: bridging robotics and neuroscience. In *Robotics Research* (pp. 617-630). Springer, Cham.

<u>Applications to healthcare technologies</u>

1. Fransvea, G., Moccia, S., Bianchi, F., Ciuti, G., Menciassi, A., Capineri, L., & Oddo, C. M. (2021, June). Intraoperative-technologies advancements in automated cancer detection: a narrative review. In *2021 IEEE International Workshop on Metrology for Industry 4.0 & IoT (MetroInd4. 0&IoT)* (pp. 128-133). IEEE.
2. Camboni, D., Massari, L., Chiurazzi, M., Caliò, R., Alcaide, J. O., D'Abbraccio, J., ... & Ciuti, G. (2020). Endoscopic tactile capsule for non-polypoid colorectal tumour detection. *IEEE Transactions on Medical Robotics and Bionics*, *3*(1), 64-73.

3. Bulletti, A., Mazzoni, M., Prasanna, S., Massari, L., Menciassi, A., Oddo, C. M., & Capineri, L. (2020). An Improved Strategy for Detection and Localization of Nodules in Liver Tissues by a 16 MHz Needle Ultrasonic Probe Mounted on a Robotic Platform. *Sensors*, *20*(4), 1183.
4. Massari, L., Bulletti, A., Prasanna, S., Mazzoni, M., Frosini, F., Vicari, E., …, Capineri, L., Menciassi, A. & Oddo, C. M. (2019). A Mechatronic Platform for Computer Aided Detection of Nodules in Anatomopathological Analyses via Stiffness and Ultrasound Measurements. *Sensors*, *19*(11), 2512.
5. D'Abbraccio, J., Massari, L., Prasanna, S., Baldini, L., Sorgini, F., Airò Farulla, G., ... & Oddo, C. M. (2019). Haptic glove and platform with gestural control for neuromorphic tactile sensory feedback in medical telepresence. *Sensors*, *19*(3), 641.
6. Sorgini, F., Massari, L., D'Abbraccio, J., Palermo, E., Menciassi, A., Petrovic, P. B., ... & Oddo, C. M. (2018). Neuromorphic vibrotactile stimulation of fingertips for encoding object stiffness in telepresence sensory substitution and augmentation applications. *Sensors*, *18*(1), 261.
7. Massari, L., D'Abbraccio, J., Baldini, L., Sorgini, F., Farulla, G. A., Petrovic, P., ... & Oddo, C. M. (2018, June). Neuromorphic haptic glove and platform with gestural control for tactile sensory feedback in medical telepresence applications. In *2018 IEEE International Symposium on Medical Measurements and Applications (MeMeA)* (pp. 1-6). IEEE.

<u>Applications to collaborative robotics for assistive technologies and industry 4.0</u>

1. Massari, L., Schena, E., Massaroni, C., Saccomandi, P., Menciassi, A., Sinibaldi, E., & Oddo, C. M. (2020). A machine-learning-based approach to solve both contact location and force in soft material tactile sensors. *Soft robotics*, *7*(4), 409-420.
2. Czimmermann, T., Ciuti, G., Milazzo, M., Chiurazzi, M., Roccella, S., Oddo, C. M., & Dario, P. (2020). Visual-based defect detection and classification approaches for industrial applications—a survey. *Sensors*, *20*(5), 1459.
3. Jovanović, K., Petrič, T., Tsuji, T., & Oddo, C. M. (2019). Human-Like Advances in Robotics: Motion, Actuation, Sensing, Cognition and Control. *Frontiers in neurorobotics*, *13*, 85.
4. Sorgini, F., Farulla, G. A., Lukic, N., Danilov, I., Roveda, L., Milivojevic, M., ... Oddo, C. & Bojovic, B. (2020, June). Tactile sensing with gesture-controlled collaborative robot. In *2020 IEEE International Workshop on Metrology for Industry 4.0 & IoT* (pp. 364-368). IEEE.
5. Massari, L., Oddo, C. M., Sinibaldi, E., Detry, R., Bowkett, J., & Carpenter, K. C. (2019). Tactile sensing and control of robotic manipulator integrating fiber Bragg grating strain-sensor. *Frontiers in neurorobotics*, *13*, 8.
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8. Prasanna, S., Massari, L., Sinibaldi, E., Detry, R., Bowkett, J., Carpenter, K., & Oddo, C. M. (2019, September). Neuromorphic tactile sensor array based on fiber Bragg gratings to encode object qualities. In *Optics and Photonics for Information Processing XIII* (Vol. 11136, p. 1113608). International Society for Optics and Photonics.

Research on Smart Materials

Integration of FBG sensors in robotic parts

Principal investigator: Fabrizio Di Pasquale

Collaborators: P. Tripicchio, S. D'Avella. C.A. Avizzano, P. Velha

Description

Modern industrial processes aim for the continuous production of small volumes tailored to the customer's needs. Machines and robotic platforms have to be more and more adaptable, flexible, and able to cope with complex scenarios where sensing and manipulation capabilities are the key technology to succeed. The literature has plenty of capacitive, resistive, piezoelectric, and piezo-resistive sensors used as tactile or force sensors. All of them present some drawbacks like non-linear behavior, sensitivity to temperature or electromagnetic noise, and hysteresis, among others. Other sensing systems are bulky and hard to integrate, sometimes jeopardizing the dexterity and manipulability of the gripper. In this context, the manuscript proposes fiber Bragg grating (FBG) optical fiber as a tactile sensing element to capture the interaction forces during material handling and object manipulation since it has numerous advantages compared with the other sensing devices. The work also offers a methodology to easily integrate the fiber in industrial grippers and introduces a set of tests useful to characterize the sensors. Custom gripper fingers have been realized in rapid prototyping to present a pictorial example of such an integration. Finally, the essay presents some experiments that assess the capability of a tactile sensor based on FBG optical fiber showing as it can correctly perceive the contact forces (NRMSE = 0.75%) and can recognize the material of the object that is being manipulated. The authors believe that the application of optical fiber sensor as tactile feedback can be useful in industrial scenarios to enable complex manipulation activities.

Related publications

1. Yonas Muanenda, Stefano Faralli, Philippe Velha, Claudio Oton, Fabrizio Di Pasquale, "Adaptable Pulse Compression in PHI-OTDR with Direct Digital Synthesis of Probe Waveforms and Rigorously Defined Nonlinear Chirping" Accepted for publication in IEEE Photonic Journals
2. Paolo Tripicchio, Salvatore D'Avella, Philippe Velha, "Towards robust grasping: an analysis of in-hand object motion with FBG optical fibers as force sensing technology", Submitted to Frontiers in Robotics and AI
3. P. Tripicchio, S. D'Avella. C.A. Avizzano, F. Di Pasquale, P. Velha, "On the integration of FBG sensing technology into robotic grippers", International Journal, Advanced Manufacturing Technology (2020), http://hdl.handle.net/11382/534822.
4. P. Tripicchio, S. D'Avella. C.A. Avizzano, F. Di Pasquale, P. Velha, "Integration of optical sensing technologies on a robotic gripper", Flexible Automation and Intelligent Manufacturing International Conference, FAIM 2020, Athens, Greece, 14-17 September 2020.

Development of FBG sensors reading units

Principal investigator: Fabrizio Di Pasquale

Collaborators: C. Oton, S. Faralli, L. Tozzetti, A. Giacobbe

Description

This research produced a high-speed Fiber Bragg Grating (FBG) interrogation based on fiber interferometry and a fast FBG sensor interrogation method based on silicon on insulator (SOI) microring resonators.

An electro-optical modulator, used as a tunable retarder, is implemented in a fiber Sagnac loop, enabling fast tuning of the interference fringes. Applying an active modulation scheme, the wavelength of the FBG can be retrieved without any requirement of the spectral position of the FBG with respect to the fringes, with no need of tunable sources or spectral analysis.

We report experimental results of wavelength measurements with a bandwidth of 100 kHz (only limited by our data acquisition rate) and a dynamic wavelength resolution of $\sigma = 3.7$ fm/$\sqrt{\text{Hz}}$ (corresponding to a strain resolution of 3.1 n$\varepsilon/\sqrt{\text{Hz}}$). We also show that the system can track a continuous tunable laser sweep of 40 nm along the C-band. The technique is polarization-independent and allows wavelength division multiplexing schemes using only one interferometer for all the sensing points. The system is fully based on low-cost off-the-shelf fiber-optical components, and the free-spectral-range of the interferometer can be easily modified by just changing the length of the polarization-maintaining fiber segment.

Also, a fast FBG sensor interrogation method based on silicon on insulator (SOI) microring resonators has been realized. The simple and effective FBG sensor interrogation scheme is based on the detection of the signal intensity at the drop port of a microring resonator, and its interrogation speed depends only on the photodetector and the front end electronics. The performance of the FBG interrogation method is evaluated in terms of minimum detectable wavelength shift and dynamic strain resolution and compared with a commercial FBG interrogator.

Related publications

1. C. Oton, L. Tozzetti, F. Di Pasquale, "High-Speed FBG Interrogation with Electro-Optically Tunable Sagnac Loops", IEEE/OSA Journal of Lightwave Technology, Vol. 38, isuue 16, pp. 4513-4519, . DOI: 10.1109/JLT.2020.2991272.
2. L. Tozzetti, T. Barsanti, F. Gambini, G. Manzo, S. Filippi, L. Matteucci, I. Izzo, F. Di Pasquale, S. Faralli, "Fiber Bragg Grating Sensors for Dynamic Strain Measurements in Gasoline Direct Injectors", IEEE Transactions on Vehicular Technology, May 2021, DOI: 10.1109/TVT.2021.3081363.
3. J. Elaskar, M. Luda, J. Codnia, and C. J. Oton, "High-speed FBG interrogator based on fiber interferometry and FPGA real-time processing" IEEE Photonics Conference (IPC) (2021).
4. J. Elaskar, M. Luda, L. Tozzetti, J. Codnia, C. J. Oton, "FPGA based high speed optical fiber sensor based on multitone mixing interferometry", (to be published in IEEE Trans. Instrumentation and Measurement, 2022).
5. C. Oton, L. Tozzetti, F. Di Pasquale, “Fast FBG Interrogation with Active Sagnac Interferometer Using Off-the-shelf Fiber Components”, 2020 OSA Optical Sensors and Sensing Congress, Vancouver, British Columbia, Canada, 22-26 June.
6. L. Tozzetti, A. Giacobbe, F. Di Pasquale, S. Faralli, "On chip fast FBG interrogator based on a Silicon on Insulator ring resonator add/drop filter”, 27th International Conference on Optical Fiber Sensors, Westin Alexandria, Alexandria, Virginia, USA, June 8-12, 2020.
7. A. Giacobbe, L. Tozzetti, F. Di Pasquale, S. Faralli, "Fast FBG sensor interrogation method based on silicon microring resonators," 2020 IEEE SENSORS, Rotterdam, Netherlands, 2020, pp. 1-4, doi: 10.1109/SENSORS47125.2020.9278705

Electrostatic Bellow Muscle actuators

Principal investigator: Marco Fontana

Collaborators: Giacomo Moretti (Univ. of Saarland, former post doc at TECIP-SSSA), Sandra Dirè (Univ. of Trento), Luca Fambri (Univ. of Trento), Ion-Dan Sirbu (Univ. of Trento), Rocco Vertechy (Univ. of Bologna).

Description

This research is about developing a novel kind of electrostatic actuator made of thin films and liquid dielectrics combined with rigid polymeric stiffening elements to form a circular electrostatic bellow muscle (EBM) unit capable of out-of-plane contraction. These units are easy to manufacture and can be arranged in arrays and stacks, which can be used as a contractile artificial muscle, as a pump for fluid-driven soft robots, or as an energy harvester.

Related publications (underlined authors with TeCIP-SSSA when paper was published)

1. Sîrbu, I.D., Moretti, G., Bortolotti, G., Bolignari, M., Diré, S., Fambri, L., Vertechy, R. and Fontana, M., 2021. Electrostatic bellow muscle actuators and energy harvesters that stack up. ***Science Robotics***, *6*(51).
2. Sirbu, I.D., Moretti, G., Vertechy, R., Dirè, S., Fambri, L. and Fontana, M., 2021, March. Electrostatic Bellow Muscle (EBM): flexible multipurpose electrostatic actuator and energy harvester based on fluid dielectric. In *Electroactive Polymer Actuators and Devices (EAPAD) XXIII* (Vol. 11587, p. 115871M). International Society for Optics and Photonics.
3. Sîrbu, I.D., Moretti, G., Bolignari, M., Fambri, L., Vertechy, R. and Fontana, M., 2021, March. Multifunctional actuators and energy harvester based on the Electrostatic Bellow Muscle (EBM). In *Electroactive Polymer Actuators and Devices (EAPAD) XXIII* (Vol. 11587, p. 115870G). International Society for Optics and Photonics. **[FIRST PLACE WINNER EAP-IN-ACTION DEMONSTRATION AWARD]**
4. Moretti, G., Duranti, M., Righi, M., Vertechy, R. and Fontana, M., 2018, March. Analysis of dielectric fluid transducers. In *Electroactive Polymer Actuators and Devices (EAPAD) XX*(Vol. 10594, p. 105940W). International Society for Optics and Photonics.

Dielectric elastomers transducers for actuation and energy harvesting

Principal investigator: Marco Fontana

Collaborators: Giacomo Moretti (Univ. of Saarland, former at TECIP-SSSA), Rocco Vertechy (Univ. of Bologna), Gianluca Rizzello (Univ. of Saarland), Stefan Seelecke (Univ. of Saarland),

Description

This research is about developing a new class of transducers based on dielectric elastomer (De) that can be employed as actuators and as generators. In actuator mode DE can offer a low-cost high-performance alternative to conventional electromagnetic actuators for robotics and small-scale mechatronic systems. As generators, DE can be a game changing technology for large scale ocean wave energy harvesting thanks to their direct drive operation and to their high power density. The research work of the group is focused to the development of novel DE actuators and generators architectures through theoretical and experimental approach.

Related publications (underlined authors are/were with TeCIP-SSA when paper was published)

1. Moretti G., Rizello G., Fontana M., Seelecke S. , Modelling and experimental characterization of voltage-driven vibrations in dielectric elastomer membranes, **Mechanical Systems and Signal Processing**, 168, 2022.
2. Righi M., Moretti G., Forehand D., Vertechy R., Fontana M., A broadbanded pressure differential wave energy converter based on dielectric elastomer generators, **Nonlinear Dyanmics**, 105, 2021.
3. Sˆırbu I.D., Moretti G., Bortolotti G., Bolignari M., Dir`e S., Fambri L., Vertechy R., Fontana M. , Electrostatic bellow muscle actuators and energy harvesters that stack up, **Science Robotics**, 6, eaaz5796, 2021.
4. Bolignari M., Rizzello G., Zaccarian L., Fontana M. , Smith-predictor-based torque control of a rolling diaphragm hydrostatic transmission, **Robotic Automation Letters**, 6 (2), 2021.
5. Moretti, G., Rizzello, G., Fontana, M. and Seelecke, S., 2021, March. A multi-domain dynamical model for cone-shaped dielectric elastomer loudspeakers. In *Electroactive Polymer Actuators and Devices (EAPAD) XXIII* (Vol. 11587, p. 115871K). International Society for Optics and Photonics.
6. Moretti G., Scialo A., Malara G., Muscolo G.G., Arena F., Vertechy R., Fontana M., Hardware-in-the-loop Simulation of Wave Energy Converters based on Dielectric Elastomer Generators, ***Meccanica***, 56 (5), 1223-1237.
7. Rizzello G., Loew P., Agostini L., Fontana M. and Seelecke S., A lumped parameter model for strip-shaped dielectric elastomer membrane transducers with arbi- trary aspect ratio, **Smart Materials and Structures**, 29 (10), 2020.
8. Moretti G., Rosset S., Vertechy R., Anderson I., Fontana M., A review on dielectric elastomer generator systems, ***Advanced Intelligent System***, 2(10), 2020.
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10. Moretti G., Sarina L., Agostini L., Vertechy R., Berselli G., Fontana M., Styrenic-Rubber Dielectric Elastomer Actuator with Inherent Stiffness Compensation, ***Actuators***, 2020, 9 (44).
11. Moretti, G., Papini, G.P.R., Righi, M., Forehand, D., Ingram, D., Vertechy, R. and Fontana, M., 2018. Resonant wave energy harvester based on dielectric elastomer generator. ***Smart Materials and Structures***, *27*(3), p.035015.
12. Papini, G.P.R., Moretti, G., Vertechy, R. and Fontana, M., 2018. Control of an oscillating water column wave energy converter based on dielectric elastomer generator. ***Nonlinear Dynamics***, *92*(2): 181-202.
13. Yi, C., Agostini, L., Fontana, M., Moretti, G. and Vertechy, R., 2018, September. On the lifetime performance of a styrenic rubber membrane for dielectric elastomer transducers. In *Smart Materials, Adaptive Structures and Intelligent Systems* (Vol. 51944, p. V001T03A028). American Society of Mechanical Engineers.

14. Moretti, G., Rosati Papini, G.P., Daniele, L., Forehand, D., Ingram, D., Vertechy, R. and Fontana, M., 2019. Modelling and testing of a wave energy converter based on dielectric elastomer generators. *Proceedings of the Royal Society A*, *475*(2222), p. 20180566.

15. Chen, Y., Agostini, L., Moretti, G., Berselli, G., Fontana, M. and Vertechy, R., 2019, March. Fatigue life performances of silicone elastomer membranes for dielectric elastomer transducers: preliminary results. In *Electroactive Polymer Actuators and Devices (EAPAD) XXI* (Vol. 10966, p. 1096616). International Society for Optics and Photonics.

16. Chen, Y., Agostini, L., Moretti, G., Fontana, M. and Vertechy, R., 2019. Dielectric elastomer materials for large-strain actuation and energy harvesting: a comparison between styrenic rubber, natural rubber and acrylic elastomer. *Smart Materials and Structures*, *28*(11), p.114001.

Electro adhesive gripper based on thin-film dielectrics

Principal investigator: Rocco Vertchy (UNIBO) and Marco Fontana (TeCIP-SSSA)

Collaborators: Tosatti, L.M (CNR), Fassi I. (CNR), Bedrozzi (Univ. Bologna)

Description

This research is about developing electro-adhesive device (EAD) that are gripping tools in which prehension forces are generated by exploiting the electrostatic attraction between charged electrical conductors of the EAD and image charges induced on the surface of the adhering object, in combination with mechanical friction. The focus of the research is on designing new devices and testing new materials and manufacturing procedure to obtain high performance reliable devices to be employed in automation industry.

Related publications (underlined authors are/were with TeCIP-SSA when paper was published)

1. Rapid Fabrication of Electro-Adhesive Devices with Inkjet Printed Electrodes, Bedrozzi N., Chen Y., Luzi L., Fontana M., Fassi I., Tosatti L., Vertechy R. ***Robotics and Automation Letters*** 5 (2), 2770-2776, 2020.
2. Caselli, M., Berdozzi, N., Agostini, L., Fontana, M., Fassi, I., Tosatti, L.M. and Vertechy, R., 2021, March. Experimental characterization of a multilayer silicone-based electroactive patch for gripper applications. In *Electroactive Polymer Actuators and Devices (EAPAD) XXIII* (Vol. 11587, p. 115871S). International Society for Optics and Photonics.

Development of exoskeleton systems for teleoperation and assistance

Principal investigator: Massimiliano Solazzi

Collaborators: Massimiliano Gabardi, Francesco Porcini, Cristian Camardella, Daniele Leonardis, Antonio Frisoli

Description

The object of the research activity is the development of robotic exoskeletons for human-machine interaction, with particular attention to motor rehabilitation and bilateral teleoperation of complex systems. This study led to the development of bimanual exoskeleton systems for the entire upper limb, capable of applying force feedback on the user's arm, hand and fingers, with a total of 12 active degrees of freedom implemented per limb. Innovative control systems and strategies are developed to guarantee stability in bilateral teleoperation and to optimize the transparency and interaction forces while using an exoskeleton

Related publications

1 C. Camardella, F. Porcini, A. Filippeschi, S. Marcheschi, M. Solazzi and A. Frisoli, "Gait Phases Blended Control for Enhancing Transparency on Lower-Limb Exoskeletons," in *IEEE Robotics and Automation Letters*, 2021 doi: 10.1109/LRA.2021.3075368.

2 Klamt, T,Schwarz, M,Lenz, C, … Gabardi, M., ... Leonardis, D., … Solazzi, M., Frisoli, A., et al. Remote mobile manipulation with the centauro robot: Full-body telepresence and autonomous operator assistance. *Journal of Field Robotics*. 2020; 37:889-919. https://doi.org/10.1002/rob.21895

3 Klamt, T., Rodriguez, D., Baccelliere, L., Chen, X., Chiaradia, D., Cichon, T., Gabardi, M., Leonardis, D., Solazzi, M., Frisoli, A. & Behnke, S. (2019). Flexible disaster response of tomorrow: Final presentation and evaluation of the CENTAURO system. *IEEE robotics & automation magazine*, *26*(4), 2019 59-72.

4 Sarac, M., Solazzi, M., & Frisoli, A. Design requirements of generic hand exoskeletons and survey of hand exoskeletons for rehabilitation, assistive, or haptic use. *IEEE transactions on haptics*, *12*(4), 2019. 400-413.

1. Soft Exosuits and Elastic Joints

Principal investigator: Antonio Frisoli

Collaborators: Domenico Chiaradia, Luca Tiseni

Description

Soft exosuits are a promising solution for the assistance and augmentation of human motor abilities in several fields, where the use of more symbiotic wearable robots can avoid excessive user fatigue and improve the quality of the work.
This research presents cable-driven based soft exosuits for upper-limb assistance. The flexible and highly compliant structures allow an optimal force transfer from the remotely located motor to the arm articulations and preserve a high level of comfort for the user during assistance.
In the same framework, we developed a soft series-viscous-elastic joint (SVEJ) suitable for integration in an exoskeleton, or a cooperative robot, or a haptic device. The proposed joint consists of 3D printed parts compressing nonlinear elastic silicone springs. The use of silicone springs is the main novelty of the system; they exhibit internal damping, which enhances system performance allowing a simpler and more stable control. SVEJ works as a torque sensor and introduces compliance between the motor and the environment, enhancing safety for robotic devices interacting with humans.

Related publications

1 Xiloyannis, M., Chiaradia, D., Frisoli, A., Masia, L., “Physiological and kinematic effects of a soft exosuit on arm movements”, in Journal of NeuroEngineering and Rehabilitation, Open Access, vol. 16, no. 1, pag. 29, 2019

2 Chiaradia, D., Tiseni, L., Xiloyannis, M., Masia, L., Frisoli, A., “An Assistive Soft Wrist Exosuit for Flexion Movements With an Ergonomic Reinforced Glove”, Frontiers in Robotics and AI, 2021, 7, 595862

3 Chiaradia, D., Tiseni, L., Frisoli, A., “Compact series visco-elastic joint (SVEJ) for smooth torque control”, IEEE Transactions on Haptics, 2020, vol. 13, no. 1, pp. 226–232, 8977380

Integration of innovative sensors in mechanical systems

Principal investigator: Massimiliano Solazzi

Collaborators: Massimiliano Gabardi, Giancarlo Santamato, Antonio Frisoli

Description

The research activity concerns the integration of innovative sensors, in particular FBG fiber optic sensors, in extended structures and functional mechanical components. The study includes the definition of the optimal positioning of the sensors, based on FEM analysis of the state of deformation under loads, and the development of technologies for applying the sensors to the mechanical structure. The interpretation of sensor measurements requires the development of analytical and numerical models, in order to estimate the static or dynamic behavior of the structure and to evaluate its functioning.

Related publications

1. Santamato, G., Chiaradia, D., Solazzi, M., and Frisoli, A. (May 11, 2020). "A Lightweight Robotic Device Based on a Micro-Macro Actuation Concept for the Inspection of Railway Pantograph." ASME. *J. Mechanisms Robotics*. December 2020; 12(6): 061002. https://doi.org/10.1115/1.4046995
2. Velha, P., Nannipieri, T., Signorini, A., Morosi, M., Solazzi, M., Barone, F., Frisoli, A.,... & Di Pasquale, F. Monitoring Large Railways Infrastructures Using Hybrid Optical Fibers Sensor Systems. *IEEE Transactions on Intelligent Transportation Systems*, *21*(12) 2019, 5177-5188.

Design of wearable haptic devices

Principal investigator: Daniele Leonardis

Collaborators: Massimiliano Gabardi, Domenico Chiaradia, Massimiliano Solazzi, Antonio Frisoli

Description

The research aims at developing innovative and effective wearable haptics devices for tactile feedback in rehabilitation, prosthetics, and teleoperation. Wearable haptics (in the shape of miniaturized actuators worn as thimbles, gloves or bracelets) can provide artificial sense of touch to the user without diminishing comfort, dexterity and workspace of movements. This is particularly relevant in certain applications where immersion of the user, comfort and minimum interferences are relevant: i.e. we experiment wearable haptic devices in neurorehabilitation settings based on immersive virtual environments. By intelligent control and mechanical design of such haptic devices, it is possible to increase quality and richness of the tactile information provided to the users, while still meeting the strict constraints in terms of reduced size and mass these devices have to comply.

Related publications

1 Bortone, I., Barsotti, M., Leonardis, D., Crecchi, A., Tozzini, A., Bonfiglio, L., & Frisoli, A. (2020). Immersive Virtual Environments and Wearable Haptic Devices in rehabilitation of children with neuromotor impairments: a single-blind randomized controlled crossover pilot study. *Journal of NeuroEngineering and Rehabilitation*, *17*(1), 1-14.

2 Cappello, L., Alghilan, W., Gabardi, M., Leonardis, D., Barsotti, M., Frisoli, A., & Cipriani, C. (2020). Continuous supplementary tactile feedback can be applied (and then removed) to enhance precision manipulation. *Journal of neuroengineering and rehabilitation*, *17*(1), 1-13.

3 Leonardis, D., & Frisoli, A. (2020). CORA hand: a 3D printed robotic hand designed for robustness and compliance. *Meccanica*, *55*(8), 1623-1638.

Testing different coatings to ensure stability and in vivo safety of NdFeB magnets implanted in muscles in a myokinetic control interface

Principal investigator: Christian Cipriani

Collaborators: Veronica Iacovacci, Irene Naselli, Alice Rita Salgarella, Francesco Clemente, Leonardo Ricotti

Description

A safe implantation of NdFeB magnets in muscles would enable the control of limb prostheses using a *myokinetic control interface* i.e., direct control of artificial limb movements by means of magnetic tracking of residual muscle contractions. However, myokinetic prosthesis control is prevented by NdFeB magnets poor biocompatibility. We thus investigated three biocompatible materials as NdFeB magnet coating candidates, namely gold, titanium nitride and parylene C, which had not been previously analyzed in a systematic way for this purpose. In vitro testing in a tissue-mimicking environment and upon contact with C2C12 myoblasts enabled assessment of the superiority of parylene C coated magnets in terms of corrosion prevention and lack of cytotoxicity. In addition, parylene C coated magnets implanted in rabbit muscles for 28 days confirmed, both locally and systemically, their biocompatibility, with a lack of irritation and toxicity associated with the implant. These findings pave the way towards a new generation of limb prostheses.

Related publications

1. Iacovacci, V., Naselli, I., Salgarella, A. R., Clemente, F., Ricotti, L., & Cipriani, C. (2021). Stability and in vivo safety of gold, titanium nitride and parylene C coatings on NdFeB magnets implanted in muscles towards a new generation of myokinetic prosthetic limbs. *RSC Advances*, *11*(12), 6766-6775.

Mechanics and Geometry of Smart Materials for Shape Morphing and Sensing

Principal investigator: Alessandro Lucantonio

Collaborators: Dario Andrini, Giovanni Noselli, Daniele Agostinelli, Antonio De Simone, Virginia Agostiniani, Danka Lucic, Ilaria Cesini, Magdalena Kowalczyk, Giacomo D'Alesio, Pramod Kumar, Domenico Camboni, Luca Massari, Pasqualantonio Pingue, Alessandro Fraleoni Morgera, Calogero Maria Oddo, Robert M McMeeking, Vikram S Deshpande

Description

Smart Materials can be employed as actuators by exploiting their ability to change shape in response to non-mechanical, external stimuli. In this research we focus on several types of smart materials, including active polymer gels, which deform because of swelling/deswelling. We investigate their peculiar fracture properties that result from their poroelastic nature and are fundamental for their successful application as actuators. Further, we derive theoretical models and implement computational tools that can be used to predict shape changes and to design actuation and sensors based on those materials. These models highlight a strong interplay between geometry and mechanics, which often offers universal results holding across multiple length scales and for diverse materials. A relatively unexplored problem that we are also tackling is the control of time-dependent shape changes, which is the fundamental feature of 4D printing techniques, i.e. 3D printing of smart materials that exhibit a programmed morphing history. In addition to polymer gels, we are interested in developing theoretical models for nanostructured piezoelectric materials for tactile sensors. Finally, among natural smart materials, we study plant shoots and specifically the growth-induced characteristic motions known as nutations, whose regulatory mechanism has yet to be understood. The study of these motions could suggest innovative designs and actuation strategies for robotic structures.

Related publications

1. Andrini, D., Lucantonio, A., & Noselli, G. (2021). A theoretical study on the transient morphing of linear poroelastic plates. *Journal of Applied Mechanics 88(3)*, 031008.
2. Cesini, I., Kowalczyk, M., Lucantonio, A., D'Alesio, G., Kumar, P., Camboni, D., Massari, L., Pingue, P., DeSimone, A., Fraleoni Morgera, A., & Oddo, C. M. (2020). Seedless Hydrothermal Growth of ZnO Nanorods as a Promising Route for Flexible Tactile Sensors. *Nanomaterials 10(5),* 977.
3. McMeeking, R. M., Lucantonio, A., Noselli, G., & Deshpande, V. S. (2020). On polymer network rupture in gels in the limit of very slow straining or a very slow crack propagation rate. *Journal of the Mechanics and Physics of Solids 136,* 103754.
4. Lucantonio, A., & DeSimone, A. (2020). Computational design of shape-programmable gel plates. *Mechanics of Materials 144*, 103313.
5. Agostinelli, D., Lucantonio, A., Noselli, G. & DeSimone, A. (2020). Nutations in growing plant shoots: The role of elastic deformations due to gravity loading. *Journal of the Mechanics and Physics of Solids 136,* 103702.
6. Agostiniani, V., Lucantonio, A., & Lucic, D. (2020). Heterogeneous elastic plates with in-plane modulation of the target curvature and applications to thin gel sheets. *ESAIM: Control, Optimisation and Calculus of Variations 25(24).*

New class of biodegradable biohybrid agents with microorganism-based energy harvesting processes for environmental monitoring

Principal investigator: Cesare Stefanini, Donato Romano

Collaborators: Abanti Afroz, Francesco Inglese, Godfried Jansen van Vuuren

Description

We propose a novel concept in robotics that allows low budget, long term, autonomous environmental monitoring to be executed by biohybrid robots. Apart from minimizing human involvement and/or interaction with the ecosystem by using autonomous biohybrid robots, we go a step further by making these robots biodegradable. Biodegradability of robots ensures that there is no long-term impact on the monitored system.
Through the use of biohybrid robots, we introduce a novel paradigm of “life form in the loop”, which will allow the development of new types of complex biohybrid entities for environmental monitoring. We will put together living organisms and technological elements using a symbiotic method to form complex entities. The salient features of these biohybrid entities are energy harvesting, low-power electronics, sensing, and actuation. Additionally, these entities will be closely integrated and the parts remaining in the environment will be fully biodegradable. The production of electric power is managed by Microbial Fuel Cells, that are colonized by local microbial life forms and use locally available organic matter as an energy source.

Related publications

1. Rajewicz, W., Romano, D., Van Vuuren, G.,J., Campo, A., Schmickl, T., Thenius, R. (2021). Freshwater organisms potentially useful as biosensors in biohybrid robotics. Biological Cybernetics. In Press.
2. Thenius, R., Rajewicz, W., Varughese, J. C., Schoenwetter-Fuchs, S., Arvin, F., Casson, A., ... van Vuuren, G., J., Stefanini, C., Romano, D., & Schmickl, T. (2021, April). Biohybrid Entities for Environmental Monitoring. In ALIFE 2021-Conference on Artificial Life. In Press.
3. Afroz, A. S., Romano, D., Inglese, F., & Stefanini, C. (2021). Towards Bio-Hybrid Energy Harvesting in the Real-World: Pushing the Boundaries of Technologies and Strategies Using Bio-Electrochemical and Bio-Mechanical Processes. Applied Sciences, 11(5), 2220.

Investigating locomotion, ultra-structures, and biochemical features of living organisms for robotics and biomedical implementations

Principal investigator: Cesare Stefanini, Donato Romano

Collaborators: Marco Miraglia, Mario Milazzo, Francesco Inglese, Paolo Dario

Description

We investigated how locusts can adapt to substrates of various roughness and compliance, thanks to a combined grasping mechanism consisting of rigid claws that generate mechanical interlocking on rough substrates, adhesive pads for vacuum adhesion on smooth substrates, and proprioception abilities. These particular characteristics can be considered as a sort of morphological intelligence, which makes locusts capable of dealing with a wide variety of substrates, even much different from each other, avoiding slipping phenomena in both jumping and landing phase.
Furthermore, we analysed the nanostructures on the wings and other organs of both hemimetabolous and holometabolous insects that can be used as a source of inspiration to design physical-based bactericidal surfaces. This biomimetic technology could represent a game changer to oppose hospital-acquired infections caused by bacteria that are susceptible to chemical resistance. Current methods to fabricate nanostructured surfaces are often focused on material for medical implants like titanium, PMMA poly (l-lactic acid) (PLLA), but this could be extended to research for, e.g., bactericidal walls, floors, bedsheets, and surgical equipment. We also report findings of how different animal species can be used as direct application and as a source of inspiration in medical engineering.
Also, we carried out studies on medicinal and aromatic plants representing an outstanding source of green active ingredients for a broad range of real-world applications. Gas chromatography coupled with mass spectrometry (GC-MS) was used to study the essential oil chemical compositions. Their use in nanoemulsion and nanoencapsulation techniques, or the employ of green coated nanoparticles can represent an environmentally sustainable approach to manage insect pests and vectors, a major and timely challenge.

Related publications

1. Bloemberg, J., Stefanini, C., & Romano, D. (2021). The Role of Insects in Medical Engineering and Bionics: Towards Entomomedical Engineering. IEEE Transactions on Medical Robotics and Bionics. Doi: 10.1109/TMRB.2021.3101693.
2. Romano, D., Bloemberg, J., McGloughlin, T., Dario, P., & Stefanini, C. (2020). Insect Ultra-Structures as Effective Physical-Based Bactericidal Surfaces. IEEE Transactions on Medical Robotics and Bionics, 2(3), 425-436.
3. Mo, X., Romano, D., Miraglia, M., Ge, W., & Stefanini, C. (2020). Effect of substrates' compliance on the jumping mechanism of *Locusta migratoria*. Frontiers in Bioengineering and Biotechnology, 8, 661.
4. Mo, X., Romano, D., Milazzo, M., Benelli, G., Ge, W., & Stefanini, C. (2020). Impact of different developmental instars on *Locusta migratoria* jumping performance. Applied Bionics and Biomechanics, 2020.
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Physical soft simulators and artificial organs

Principal investigators: Matteo Cianchetti and Arianna Menciassi

Collaborators: Cecilia Laschi, Martina Maselli, Arianna Conte, Debora Zrinscak, Lucrezia Lorenzon, Mauro De Luca, Sabina Maglio, Selene Tognarelli

Description

Soft robotics is demonstrating that the use of soft materials to develop robotic systems is possible and bringing some advantages in some cases with respect to more traditional approaches based on rigid materials. One of the most promising research fields that are exploiting these advantages is related to the possibility to replicate the functionality of soft tissues of living beings. In particular, this is possible at two different levels: physical simulators, that are able to reproduce organ functionality and that can be used to study physio-pathological conditions; artificial organs, that besides replicating the physiological functionality, it also needs to face issues related to biocompatibility for implantation.

More specifically, on the first topic, the group is developing several soft simulators both for clinical training and testing. An artificial larynx, at the moment focusing on the reproduction of the glottis plane (vocal folds) has been realized to provide clinicians with a testing platform where the correlation between geometrical/mechanical characteristics and vocal product can be studied. This implied the reproduction of the biomechanical features of the vocal folds and their vibration behaviour in both physiological and pathological conditions. A high-fidelity neonatal pneumothorax simulator was developed and assessed by exploiting the strict collaboration between engineers and neonatologists and the large availability of residents. Simulating the pneumothorax means reproducing the pleural space, i.e., an airtight chamber delimited by the lung, diaphragm, chest wall and mediastinum. All these structures were reproduced in the simulator through additive and formative manufacturing technologies and using materials that try to simulate the mechanical properties of human tissues. The simulator presents a compliant thermoplastic polyurethane neonatal ribcage incorporated into a silicone chest wall, two lungs, a heart, a mediastinum and two dedicated areas for the needle insertion in the 3rd intercostal space. A simulated diaphragm was realized and glued to close the left and right pleural space at the manikin bottom and to connect them to the simulator hardware. Head, arms and a cover skin were then added to make the training procedure as realistic as possible. Through intensive testing sessions with expert and non-expert neonatologists, the simulator validity as teaching and retraining tool for both local and remote training was demonstrated.

On the second topic, we are developing a fully soft artificial heart. The heart is a vital organ, and its main functionality is almost purely mechanical. It is completely made of soft tissues and thus fully in scope for the exploitation of soft mechatronic technologies. We are currently pursuing different approaches to restore pulsatile functionality: one more biomimetic (trying to understand the functional arrangement of natural muscle fibres) and one more mechanically optimized (exploiting structural instabilities to obtain a leverage effect that increases ejection capability).

Related publications

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Soft continuous arms and grippers

Principal investigator: Matteo Cianchetti

Collaborators: Cecilia Laschi, Martina Maselli, Shadab Zaidi, Luca Arleo, Arianna Menciassi, Giacomo Picardi, Egidio Falotico, Selene Tognarelli

Description

Soft robotics technologies demonstrated the capability to introduce a new paradigm in the development of robotic devices and in particular in the application scenarios where dexterity and intrinsic safety are of paramount importance. The peculiar characteristics of soft mechatronic devices make them very good candidate in the framework of robotic surgery. We developed a series of manipulators with mechanical characteristics and performance suitable for abdominal endoscopy and surgery. These devices have the capability of bending omnidirectionally and elongate and at the same time, they can safely interact with the surrounding tissues, being fully made of soft materials. Nevertheless, when necessary, the latest versions of the device demonstrate the possibility to locally increase their stiffness, increasing stability and force propagation to enable more intrusive surgical procedures.
Assistive robotics is another example where soft mechatronics can play an important role. In this context, we developed a modular soft arm, able to support the user in bathing activities. A soft robotic arm able to act as a robotic shower effectively, yet safely (both from a mechanical and electrical point of view).
More recently, the experience gained in the development of soft continuous structures has been also applied to soft grippers for delicate manipulation, especially in the context of food handling.

Related publications

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Soft mechatronic technologies

Principal investigator: Matteo Cianchetti

Collaborators: Cecilia Laschi, Martina Maselli, Paolo Dario, Selene Tognarelli

Description

Soft Robotics is an emerging field of robotics that reconsidered the role of material properties of components of a robot body. In particular, it undermines the idea that a robot should be made of rigid materials. Soft materials do have characteristics and potential to be used to develop entire robots with very advanced motion capabilities and nature shows this very clearly with animals like octopuses.
However, this new field is still at its infancy and many efforts are required, especially in the development of basic and enabling technologies. We are very active especially in the development of new kind of actuators, sensors, and mechanisms, based on soft and/or flexible materials and able to change their stiffness when required.

Related publications

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Shape programming for smart materials and deployable structures

Principal investigator: Antonio De Simone

Collaborators: Jacopo Quaglierini, Alessandro Lucantonio, Daniele Agostinelli, Virginia Agostiniani, Giancarlo Cicconofri, Giovanni Corsi, Giovanni Noselli, Davide Riccobelli, Marino Arroyo, Benoit Roman, Ryan Hayward

Description

Deployable structures are defined by the possibility of changing configuration and shape from the one most convenient for transportation, to the one required by its function. Smart Materials can be employed as actuators by exploiting their ability to change shape in response to external stimuli. Our research activities in these fields are at the forefront of recent efforts from the international community whereby new morphing concepts are obtained by the interplay of geometry and mechanics, often following bio-inspiration from biological organisms (from both the animal and plant kingdoms). We typically derive theoretical models and implement computational tools that can be used to predict shape changes and to design actuators and sensors based on smart materials. For example, we have demonstrated the use of active shearing and stretching as an application of the Gaussian morphing principle (i.e., shape control by modulation of active stretches induced on a flexible surface) to propose innovative morphing mechanisms in a variety of systems, spanning a wide range of length scales (from micrometer to meter) and materials (from liquid crystal elastomers to inflatable fabrics). The results of these studies suggest innovative designs and novel actuation strategies for soft robotic structures.

Related publications

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Design principles for bio-inspired microrobots: a two-way interaction between biology and engineering

Principal investigator: Antonio De Simone

Collaborators: Jacopo Quaglierini, Giancarlo Cicconofri, Giovanni Corsi, Giovanni Noselli, Marino Arroyo, Gerhard Gompper, Jay Humphrey, Ellen Kuhl, Robert McMeeking, Vikram S Deshpande, Alain Goriely, Pierre Recho

Description

The ability to move is one of the key functional requirements for robots and is, at the same time, one of the hallmarks of living organisms. We study motility and locomotion in biological organisms (from cells and unicellular organisms to more complex living systems such as growing plant shoots) to learn and distill motility principles thanks to the combination of experimental observation, theoretical modeling, and numerical simulation. We then examine how these principles explain the successful performance of living creatures, and how they can offer inspiration for innovative robotic constructs, especially at small scales. Examples of systems for which our approach has been particularly successful are Euglenids (a family of unicellular algae), swimming organisms moving in a fluid by flagellar beating or peristaltic waves, contact guidance in crawling cells, nutations in growing plant shoots.

Related publications

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Implantable, wearable and portable mechano-electrotransducers

Principal investigator: Calogero Maria Oddo

Collaborators: *Intra department.* Domenico Camboni, Maria Chiara Carrozza, Ilaria Cesini, Giacomo D'Alesio, Jessica D'Abbraccio, Antonio De Simone, Mariangela Filosa, Marco Fontana, Giulia Fransvea, Pramod Kumar, Alessandro Lucantonio, Luca Massari, Mario Milazzo, Cesare Stefanini, Giuseppe Terruso. *External.* Andrea Aliperta, Michele Arturo Caponero, Marco Di Rienzo, Federica Durini, Carlo Massaroni, Maurizio Ferrarin, Domenico Formica, Alessandro Fraleoni Morgera, Eduardo Palermo, Pasqualantonio Pingue, Maria Sabrina Sarto, Emiliano Schena, Helge A. Wurdemann

Description

This line of research addressed the development of implantable, wearable and portable mechanoelectrotransducers by means of chemical-physical fabrication processes, their integration within soft polymeric materials, and the application of FEM modelling methods. The technologies developed were based on the fabrication and integration of Fiber Bragg Grating photonic tactile sensors, of Zinc Oxyde Nanorods with custom seedless hydrothermal method, and on the design of components fabricated with micromachining, 3D printing and bioprinting equipment. Their characterization involved the use of instrumentation such as AFM, SEM, SPM and other microscopy tools. Targeted applications included biomechanical and bioelectronic cardio-respiratory monitoring in clinical, work and sport scenarios, smart tactile sensors and haptic interfaces that could be integrated within large and flexible surfaces, and transducers for renewable energy harvesting in green economy.

Related publications

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Smart materials for endowing biomedical devices with enhanced properties

Principal investigator: Leonardo Ricotti

Collaborators: Lorenzo Vannozzi

Description

This research line addressed the development of smart materials (in some cases also including living cells) for endowing biomedical devices with enhanced properties. This concerned the development of hybrid artificial-biological materials for implant and tissue regeneration, synthetic tissue substitutes for mimicking natural tissues/organs features but also for the development of non-conventional robots, and the use of advanced materials for developing tissue/organ-mimicking set-ups on which the efficacy of different biomedical technologies could be verified.

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Wearable Robotics: design, development, and validation of novel exoskeletons and lower-limb prostheses

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Description

Wearable Robotics (WR) is the research area focusing on the design and development of exoskeletons and prostheses, also called wearable robots. Wearable robots can help people to regain and strengthen their movements. Such robots are worn by humans to replace or improve a body function, which has suffered a damage, or they can be used as a training device to allow people to move again, or they can be used to augment human movement capabilities. WR's applications include neuro-motor rehabilitation, daily-life activities assistance, workers' assistance in occupational scenarios.

We designed and developed novel mechatronics solutions for upper- and lower-limb powered exoskeletons, as well as lower-limb prostheses, with the goal of obtaining wearable robots which could be potentially effective in both rehabilitation and assistive scenarios. Such devices target neurological subjects (e.g., post-stroke patients) or amputees and elderly subjects, namely people with limited mobility. To achieve this objective, we designed lightweight and compact but also powerful actuators to match the requirements of usability and effectiveness.

Besides, we designed and developed novel algorithms for intuitive and effective control of the wearable robots we developed. Such algorithms were mainly used for understanding users' motion intentions to allow the wearable robots to timely and efficiently deliver the assistive action while performing gait-related tasks in case of lower-limb exoskeletons/prostheses or lifting objects in case of lumbar exoskeletons in occupational scenarios.

We performed several clinical trials with amputees and post-stroke patients and laboratory experimentations with healthy subjects. Such activities were important to prove the validity of the scientific hypotheses at the basis of the development of our wearable robotics prototypes and control strategies.

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