PhD in Information Technology and Electrical Engineering

Università degli Studi di Napoli Federico II

PhD Student: Sunny Katyara

XXXIV Cycle

Training and Research Activities Report – Third Year

Tutor: Prof. Bruno Siciliano

1. INFORMATION

I, Sunny Katyara, holding M.Sc in Control Engineering from Wroclaw University of Science and Technology Poland – July 2018. I have completed three years of a joint PhD between the Universita di Napoli Federico II (UNINA) and Istituto Italiano di Technologia (IIT), supervised by Prof. Bruno Siciliano (UNINA) and Prof. Darwin G. Caldwell (IIT).

2. STUDY AND TRAINING ACTIVITIES

Courses:

Lecture/Activity	Type	Credits	Certification	Notes
Cognitive Robotics for Human-Robot Interaction	Ad hoc module	6.0	×	PhD course by UNIGE

Seminars:

Lecture/Activity	Type	Credits	Certification	Notes
Social Isolation and Its Impact on the Human Brain	Seminar	0.5	×	IIT Seminar
Building Career in Non-academic Contexts	Seminar	0.5	×	IIT Seminar
How to Publish your research in Nature and the Nature Research Journals	Seminar	0.5	×	IIT Seminar
Medical Device Regulation: Next Steps	Seminar	0.5	×	IIT Seminar
Marine Robotics Challenges and Applications	Seminar	0.5	×	IIT Seminar
Research Ethics	Seminar	0.5	×	IIT Seminar
The Era of Human-	Seminar	0.6	×	ITEE UNNIA

Robot Collabotaion: Deep Sea Exploration				Seminar
The path to Autonomous Functions in Robot Assisted Surgery	Seminar	0.6	×	IIT Seminar
Robotics Goes PRISMA	Seminar	0.6	×	IIT Seminar

External Courses:

None

3. RESEARCH ACTIVITY

My major research direction is formulating and learning control for fine manipulation. The term, formulating and learning control, refers to the process of defining and acquiring control laws to solve different robotic tasks. The robotic tasks considered include agricultural pruning, collaborative assembling/disassembling, pouring and screwing, pushing and pulling, orienting and pressing, and handling of non-rigid objects, which all in common require the fine regulation of robot movements and interaction forces, to not only achieve a coordinated motion control but also to avoid damage to object or the robot itself. Therefore, to achieve a fine manipulation behavior for the robotic tasks, the ideas of hierarchical and cognitive control formulation and the Bayesian inference learning using movement primitives are exploited to come up with the optimal control policies and probabilistically encoding them accordingly.

To summarize, the key obectives of my PhD research include;

i. To propose a multi-modal control framework for automating the pruning of dynamic agricultural plants. The framework need not to only plan an optimal path for a non-holonomic robot platform but also prioritize its movements according to the task constraints and as well as ensures flexible interactions with the environment.

ii. To formulate an intuitive hierarchical controller for human robot collaboration by considering the human postures and task progression. The controller needs to adapt to the dynamics of tasks and as well as the varying gestures of human subject in the collaborative environments.

iii. To derive a synergistic control law for an anthropomorphic robot hand to reproduce different precision grasping and in-hand manipulation postures. The control law needs to be simple and generic so that it can be easily applied to different design variants of the robot hands.

iv. To learn and encode the derived synergistic control policy to enable it to be reused for robust grasping and fine manipulation of different daily life objects. The resultant learned control policy, which is coined as Kernelized Synergies, needs to be task agnostic and also ensures the global grasp stability.

v. To augment the Kernelized Synergies framework using visuo-tactile information to improve its autonomy and flexibility in interacting with rigid and non-rigid objects. The upgraded framework needs to infer the current states of the environment robustly and modulate its environmental descriptors accordingly.

vi. To assess the performance of the Kernelized Synergies framework against the other state-of-art methods and as well as by trying the various valid kernel functions. It needs to be quantified by using different numerical evaluation metrics such as; normalized squared error, primitive accuracy, root mean squared error and correlation coefficient.

In the **first year,** I spent my first quarter on making thorough literature survey on controls for fine manipulation in-terms of design and formulation of active robot controllers for error (i.e, twist/wrench) compensation, the presence and contribution of task constraints and system compliance for modulation (i.e, obstacle or singularities) and model-based learning for fine motion control considering the methods for location of candidate objects, the criterion for selection of best stable grasp, the algorithms for grasp planning and optimization, and the approaches for motion and interaction control. In the next two quarters, to get aquited with the required set of skills to design and encode adaptive, intuitive and efficient control policies, the different tools i.e, Kinemeatic-Dynamic modeling of Rigid bodies for force controls, constrained QP for motion planning, depth and haptic sensors for environment perception, visual servoing for task monitoring and autonoumous interaction, MoveIt for manipulation planning, ROS for effective communication with robot interfances, Blender for 3D modeling and rendering, Syngrasp toolbox for synergistic grasp evaluation, Pytorch and OpenAI Gym for sim2real skill transfer, Probabltic learning for task imitation and generalization, and many others, just to mention majors.

Finally, in the last quarter, to apply and test the learnt skills, the fine manipulation task, i.e, robot pruning was chosen as a case study. The pruning is one of the fine manipulation tasks which requires the high-level of precision to increase the quantity and quality of the yield produced. The Cartesian tasks for the pruning scenarios were defined in terms of task Jacobian and task errors having asymptotic convergence. All the task were stacked together into a hierarchical architecture and were assigned with priorities to weight their absolute and relative actions. The entire stack-of-tasks was solved using the constrained Quadratic Programming (QP) that did not only generate optimal solution in terms of joint trajectories but also ensured that the limits on joints' positions and velocities were not being violated while executing the given tasks. Further, to achieve flexible and adaptive interactions with the vine branches either in rest or moving, the solution from QP was sent to the Natural Admittance Controller as a reference trajectory, that enabled the force regulation at the End-Effector of the robot arm by properly selecting the values of desired compliance and minimizing the error between the desired force and the measured force from the force/torque sensor at the Cartesian level. In this scenario, the perception of environment was made through the depth information that monitored the agricultural field and helped to locate the spurs initially and then the potential pruning points on the candidate grape vines, that were detected using the trained Faster R-CNN network together with the graph morphometry algorithm. The entire setup was evaluated on the simulated vineyard and as well as using the real system at the laboratory level. The results obtained showed that the proposed framework achieved the desired pruning accuracy (i.e, compared to the ground truth), with fewer cutting actions and better execution time. From this analysis, a paper was accepted at 13th Workshop on Human Friendly Robotics (HFR 2020) and was given

Best Research Paper Award by Franka-Emika, Germany and also being selected for publication into Springer Proceedings on Advanced Robotics (2021).

In the **second year**, during the first three quaters, the above formulation, evaluated on agricultural scenario, was modified and extended to intuitive human-robot collaboration (iHRC). However, the nature of tasks considered for iHRC was different but the fundamental idea of defining the stack-of-tasks and exploiting the constrained QP for its optimal solutions were consistent. In this study, the idea of intuitive HRC was exploited, which is the blend of cognitive (non-contact) and physical (contact) collaborations between the human and robot. Considering the dual nature of iHRC, the two types of primary tasks were defined i.e, the Cartesian and the force based tasks. The Cartesian tasks were responsible for bringing the robot to a desired configuration in the task space whereas the force-based tasks were used to regulate the grip strength to achieve a desired stability and task accuracy. Further, for each of the primary tasks defined in stack, two important secondary tasks i.e, the manipulability measure and the joint limit avoidance were defined as well. The switching between the sub-tasks within the formulated stack occurred intuitively by taking into account the varying human postures and task progression, determined using the visuo-tactile perception in a traded fashion. By considering the Kineto-Static duality between the velocity and force subspaces and as well as assuming an ideal dynamics of the system, the force applied at the jaws of gripper during the grasping and manipulation phases were regulated by the tactile feedback. Whereas, the external forces experienced at the End-Effector level during the task execution were compensated by the respective velocities at the joint level. The performance and effectiveness of the proposed framework was assessed against the traditional human-human cooperation for the assembly and disassembly tasks. The comparative analysis validated that the proposed formulation had better task execution, repeatability, grasp adaptation and precision but unfortunately suffered from coordination latency due to the fusion and utilization of different sensing modalities that were operating at different loop rates. The results from this investingation have been submitted to **IEEE Transactions on Human-Machine Systems** and the manuscript is currently under review.

In the last quater, considering the technology driven nature of above proposed formulations, a neuro-scientific approach, called postural synergies was adopted to emulate the functionalities and capabilities of the human hand. The idea of Postural Synergies so far has been successfully applied to grasping scenarios and its extension to manipulations remained unfeasible due to the need for using more extra synergistic components, which violate the prime motivation behind using it i.e, bringing simplicity. However, we have managed to extend them to simple in-hand manipulation tasks. The basic idea involved, tele-operating the robot hand for grasping initially and recording its corresponding joint configurations. Later, the grasp configurations were taken as reference for the manipulations (i.e, the difference between the grasping and final manipulation postures as a regulation task), the associated joint configurations were collected into another configuration matrix. Both, the grasping and manipulation configuration matrices were concatenated into a block-partioned matrix. The PCA was applied onto the resultant block-partioned matrix and the vectors governing the directions of highest variances were chosen, which defined the Eigen-grasps or the Postural Synergies of the robot hand. The four synergistic components (i.e selected by imposing the criteria of 85\% variance) were able to actuate 6 DoF and achieved under-actuation of the fully actuated robot hand. Although, the proposed formulation was a nice approximation for reproducing the taught postures in a synergistic manner by exploiting the interpolation property but it was unable to generalize to new objects or tasks due to the lack of extrapolation. Also, the proposed formulation was best suited for free motion posture evaluation because it did not take into account the forces exerted on the object during grasping and manipulation. However, this formulation was not an optimal solution for complex manipulation tasks because the number of synergistic components rose proportionally but it laid the nice foundation for extending them to manipulations as well. It definitely required some empirical model-based approach to overcome all the limitations associated with this formulation and develop a new framework that could address the fine manipulation problem.

In the **third year**, during first two quaters, the limitations associated with the above analytically determined Postural Synergies for manipulation, were addressed by exploiting the model-based empirical approach to learn them probabilistically for task reproduction and generalization. The resultant framework was coined as Kernelized Synergies, owing to the use of Kernel trick. In the proposed framework, after determining the Postural Synergies analytically, they were evolved over the duration of demonstrations to obtain the corresponding synergistic trajectories. The resultant synergistic trajectories were approximated using the Gaussians and the corresponding mixture model from all the trajectories was retrieved. The model was conditioned over the time, to generate a reference trajectory such that all the taught postures could be reproduced by exploiting this reference synergistic trajectory at different time instants. However, yet it was unable to generalize to new objects but being probabilistic in nature, it could adapt to different dimensions of same objects. To enable it to generalize to different objects and tasks, the idea of Kernelized Movement Primitives was exploited that endowed the probabilistic synergistic subspace to extrapolate, modulate and superimpose to achieve desired behavior for the unknown conditions. However, the resultant parametric synergistic trajectories were able to generate motion commands for new conditions as the environmental descriptors but still were unable to consider the regulation of interaction forces during grasping and manipulation. Therefore the parametric synergistic components, obtained after the kernel treatment of probabilistic synergistic trajectories, were given to the model of soft synergies that ensured the contact compliance by exploiting the joint stiffness of the robot hand. In this way, the Kernelized Synergies framework was able to generate the complaint grasps. Further, the stability of the established grasps was evaluated using the customized force closure grasp quality index under distinct interaction scenarios. The Kernelized Synergies framework was examined using different dexterous simulated and real robot hand models for various commercial tasks and it was found that the set of two Kernelized Synergies were able to achieve all the presented fine manipulation behaviors. The results of this approach has been published into **IEEE Transaction of Cognitive and Development Systems**.

Later, in the next two quaters, the autonomy and flexibility of the Kernelized Synergies framework was improved for run-time object location and exploration. The framework was augmented using visuo-tactile feedback and all the sensory feedback quantities were transformed into respective synergistic values to modulate the environmental descriptors i.e, via and end points of the Kernelized Synergies framework. The upgraded framework owing to its improved intelligence and adaptability, was applied to robust grasping and fine manipulation of non-rigid objects by precisely regulating the contact forces and motions to impart desired behaviors to the delicate objects, where the compliance was ensured by the model of soft synergies. Further, the Kernelized Synergies framework was evaluated against the other approaches using two metrics i.e, the normalized mean squared error and the primitive accuracy and it was found that the Kernelized Synergies framework achieved desired task precision and execution by exploiting least number of synergistic components. Also, the performance and potential of the Kernelized Synergies framework was assessed using different valid kernel functions i.e, Exponential, Gaussian and Cauchy, against the synergistic re-usability, task execution, repeatability and generalization. It was found that the Cauchy kernel having long-term memory effects and temporal mixing regulation gave better results in terms of root mean squared error and co-relation coefficient. The partial outcomes of this study has been published into **2021 IEEE Conference on Robotics and Automation (ICRA 2021)**.

Finally, in the last fifth quater, with the requested extension of three months, the write and compilation of PhD thesis was majorly carried out.

All the research activities during the PhD studies have been carried out between the PRISMA LAB at UNINA and the ADVR at IIT.

4. PRODUCTS

Publications (published/submitted):

i. S. Katyara, F. Ficuciello, D. G. Caldwell, F. Chen, and B. Siciliano. "Reproducible pruning system on dynamic natural plants for field agricultural robots." 13th International Workshop on Human-Friendly Robotics, pp. 1-15. Springer, Cham, 2020. [Published]

Abstract: Pruning is the art of cutting unwanted and unhealthy plant branches and is one of the difficult tasks in the field robotics. It becomes even more complex when the plant branches are moving. Moreover, the reproducibility of robot pruning skills is another challenge to deal with due to the heterogeneous nature of vines in the vineyard. This research proposes a multi-modal framework to deal with the dynamic vines with the aim of sim2real skill transfer. The 3D models of vines are constructed in blender engine and

rendered in simulated environment as a need for training the network. The Natural Admittance Controller (NAC) is applied to deal with the dynamics of vines. It uses force feedback and compensates the friction effects while maintaining the passivity of system. The faster R-CNN trained on 3D vine models, is used to detect the spurs and then the statistical pattern recognition algorithm using K-means clustering is applied to find the effective pruning points. The proposed framework is tested in simulated and real environments.

ii. S. Katyara, F. Ficuciello, D. G. Caldwell, B. Siciliano and F. Chen, "Leveraging Kernelized Synergies on Shared Subspace for Precision Grasping and Dexterous Manipulation," in IEEE Transactions on Cognitive and Developmental Systems, doi: 10.1109/TCDS.2021.3110406. [Published]

Abstract: Manipulation in contrast to grasping is a trajectorial task that needs to use dexterous hands. Improving the dexterity of robot hands, increases the controller complexity and thus requires to use the concept of postural synergies. Inspired from postural synergies, this research proposes a new framework called kernelized synergies that focuses on the re-usability of same subspace for precision grasping and dexterous manipulation. In this work, the computed subspace of postural synergies is parameterized by kernelized movement primitives to preserve its grasping and manipulation characteristics and allows its reuse for new objects. The grasp stability of proposed framework is assessed with the force closure quality index, as a cost function. For performance evaluation, the proposed framework is initially tested on two different simulated robot hand models using the Syngrasp toolbox and experimentally, four complex grasping and manipulation tasks are performed and reported. Results confirm the hand agnostic approach of proposed framework and its generalization to distinct objects irrespective of their dimensions.

iii. S. Katyara, F. Ficuciello, F. Chen, B. Siciliano and D. G. Caldwell, "Vision Based Adaptation to Kernelized Synergies for Human Inspired Robotic Manipulation," 2021 IEEE International Conference on Robotics and

Automation (ICRA), 2021, pp. 6491-6497, doi: 10.1109/ICRA48506.2021.9561046. [Published]

Abstract: Humans in contrast to robots are excellent in performing fine manipulation tasks owing to their remarkable dexterity and sensorimotor organization. Enabling robots to acquire such capabilities, necessitates a framework that not only replicates the human behaviour but also integrates the multi-sensory information for autonomous object interaction. To address such limitations, this research proposes to augment the previously developed kernelized synergies framework with visual perception to automatically adapt to the unknown objects. The kernelized synergies, inspired from humans, retain the same reduced subspace for object grasping and manipulation. To detect object in the scene, a simplified perception pipeline is used that leverages the RANSAC algorithm with Euclidean clustering and SVM for object segmentation and recognition respectively. Further, the comparative analysis of kernelized synergies with other state of art approaches is made to confirm their flexibility and effectiveness on the robotic manipulation tasks. The experiments conducted on the robot hand confirm the robustness of modified kernelized synergies framework against the uncertainties related to the perception of environment.

Publications (Under Review):

i. S. Katyara, N. Deshpande, F. Ficuciello, F. Chen, B. Siciliano and D. G. Caldwell, "Fusing Visuo-Tactile Perception into Kernelized Synergies for Robust Grasping and Fine Manipulation of Non-rigid Objects," [\url{https://arxiv.org/abs/2109.07207}]

Abstract: Handling non-rigid objects using robot hands necessitates a framework that does not only incorporate human-level dexterity and cognition but also the multi-sensory information and system dynamics for robust and fine interactions. In this research, our previously developed kernelized synergies framework, inspired from human behaviour on reusing same subspace for grasping and manipulation, is augmented with visuo-tactile perception for autonomous and flexible adaptation to unknown objects. To detect objects and estimate their poses, a simplified visual pipeline using RANSAC algorithm with Euclidean clustering and SVM classifier is exploited. To modulate interaction efforts while grasping and manipulating non-rigid objects, the tactile feedback using T40S shokac chip sensor, generating 3D force information, is incorporated. Moreover, different kernel functions are examined in the kernelized synergies framework, to evaluate its performance and potential against task reproducibility, execution, generalization and synergistic re-usability. Experiments performed with robot arm-hand system validates the capability and usability of upgraded framework on stably grasping and dexterously manipulating the non-rigid objects.

ii. S. Katyara, N. Deshpande, F. Ficuciello, T. Teng, B. Siciliano, D. G. Caldwell, and F. Chen "Formulating Intuitive Stack-of-Tasks using Visuo-Tactile Perception for Collaborative Human-Robot Fine Manipulation," in IEEE Transactions on Human-Machine Systems, 2022 [\url{https://arxiv.org/abs/2103.05676}].

Abstract: Enabling robots to work in close proximity to humans necessitates a control framework that does not only incorporate multi-sensory information for autonomous and coordinated interactions but also has perceptive task planning to ensure an adaptable and flexible collaborative behaviour. In this research, an intuitive stack-of-tasks (iSoT) formulation is proposed, that defines the robot's actions by considering the human-arm postures and the task progression. The framework is augmented with visuo-tactile information to effectively perceive the collaborative environment and intuitively switch between the planned sub-tasks. The visual feedback from depth cameras monitors and estimates the objects' poses and human-arm postures, while the tactile data provides the exploration skills to detect and maintain the desired contacts to avoid object slippage. To evaluate the performance, effectiveness and usability of the proposed framework, assembly and disassembly tasks, performed by the human-human and human-robot partners, are considered and analyzed using distinct evaluation metrics i.e, approach adaptation, grasp correction, task coordination latency, cumulative posture deviation, and task repeatability.

5. CONFERENCES AND SEMINARS

I. 2021 IEEE International Conference on Robotics and Automation (ICRA) May 30 - June 5, 2021, Xi'an, China
II. ICRA Workshop ViTac 2021: Trends and Challenges in Visuo-Tactile Perception

6. ABROAD ACTIVITY

None

7. TUTORSHIP

None

8. SUMMARY OF CREDITS

Student: Sunny Katyara sunny.sunny@unina.it | Tutor: Bruno Siciliano bruno.siciliano@unina.it | Cycle XXXIV

	Credits year 1								Credits year 2								Credits year 3									
	Estimated	bimonth 1	bimonth 2	bimonth 3	bimonth 4	bimonth 5	bimonth 6	Summary	Estimated	bimonth 1	bimonth 2	bimonth 3	bimonth 4	bimonth 5	bimonth 6	Summary	Estimated	bimonth 1	bimonth 2	bimonth 3	bimonth 4	bimonth 5	bimonth 6	Summary	Total	Check
Modules	15			6	6.6			12.6	25			0	8	12.6	5	25.6	10				6			6	44.2	30-70
Seminars	5			0.8		0.8	0.8	2.4	2			2	0.5	0.5		3	5	0.5	0.5	1	0.5	0.5	1.8	4.8	10.2	10-30
Research	40	6	7	6	7	9	9	44	50	5	5	6	10	10	10	46	55	7	6	10	10	12	15	60	150	80-140
	60	6	7	12.8	13.6	9.8	9.8	59	77	5	5	8	18.5	23.1	15	74.6	70	7.5	6.5	11	16.5	12.5	16.8	70.8	204	180

Training and Research Activities Report – Third Year

PhD in Information Technology and Electrical Engineering – XXXIV Cycle

Sunny Katyara

Year	Lecture/Activity	Type	Credits	Certification	Notes
1	Robotics for Bio-Engineering	MS Module	6	x	
1	Machine Learning	Ad hoc module	4.2	x	
1	Methods for Explainable Machine Learning	Ad hoc module	2.4	x	
1	Active perception and robot Interactive learning	Seminar	0.4	x	
1	Robotics in medical applications	Seminar	0.4	x	
1	Complexity trade-offs for robot motion and manipulation skills	Seminar	0.4	x	
1	Development of non-contact measurement techniques for qualification of additive manifactured robotic components	Seminar	0.4	x	
1	Continual learning for robotics	Seminar	0.4	x	
1	Identification and model based control of robots	Seminar	0.4	x	
1	Robotic cognitive adaptive system for teaching and learning	Seminar	0.4	x	
2	Mathematics of Finite Element Method	Ad hoc module	4	x	
2	Design and Implementation of AR Software System	Ad hoc module	4	x	
2	C++ Programming Techniques	Ad hoc module	6	x	
2	Strategic Orientation for STEM Research and Writing	Ad hoc module	6.6	x	
2	Grant Writing	Ad hoc module	5	x	
2	Computational Biology	Seminar	0.5	x	
2	Large Scale Training of Deep Neural Networks	Seminar	0.5	x	
2	Regularization Methods for Machine Learning	Summer School	2	x	
3	Cognitive Robotics for Human-Robot Interaction	Ad hoc module	6	x	
3	Social Isolation and Its Impact on the Human Brain	Seminar	0.5	x	
3	Building Career in Non-academic Contexts	Seminar	0.5	x	
3	How to Publish your Research in Nature and the Nature Research Journals	Seminar	0.5	x	
3	Medical Device Regulation Next Step	Seminar	0.5	x	
3	Marine Robotics Challenges and Applications	Seminar	0.5	x	
3	Research Ethics	Seminar	0.5	x	
3	The Era of Human-Robot Collaboration: Deep Sea Exploration	Seminar	0.6	x	
3	The Path to Autonomous Functions in Robot Assisted Surgery	Seminar	0.6	x	
3	Robotics Goes PRISMA	Seminar	0.6	x	