Research activities at MMSA lab of the University of Padova

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In this paper, the activities of the laboratories of the group of Mechanism and Machine Science and Applications (MMSA) of the University of Padova are reported.

The labs activities focus on the applied research on numerous fields, such as energy harvesting technologies, vehicles, industrial robots, drones with manipulators and collaborative robotics.

This paper presents the current research activities as well as the experience on topics that can be useful not only in the research field but also for training new generations of engineers and researchers.

1. Introduction

One of the most difficult aspects about the collaboration between different research institutions is to know and understand which are the research and teaching activities of the other institutions. This problem can be fostered during conferences, in which different researchers meet and create new connections.

However, the activities of the research groups are rarely recorded in publications. Some research groups summarize the activities in websites, but such websites are sometimes not updated and may lack some information, especially the one related to the teaching activities. Moreover, once the website is updated there is rarely any evidence of the previous states.

In this paper, a survey is presented on the activities that have been recently carried out at the MMSA group in Padova, with the aim to encourage future collaboration at different levels.

2. The laboratories at the University of Padova

Thanks to the broad research field, the MMSA group has at its disposal several laboratories, in which several devices are available and in which several research activities are carried out.

2.1. Robotics lab

The Robotics lab consists of two open spaces in which several devices are installed.

In the first open space contains the small devices which can be used for small researches: industrial cameras, 3D printers, haptic devices and informatics hardware.

In the second open space the bigger devices are installed. This lab contains 5 industrial robots, of which 3 SCARA robots, 1 parallel robot and 1 6-axis robot, as well as 1 collaborative robot. All of the industrial robots are installed in dedicated workcells in which are available several devices to help the researches in their daily activities, such as benches with Item profiles on which devices can be easily installed and moved. In the same lab is installed a Cable-driven robot, which has a dedicated workspace.

Up to 16 students can join the lab for the teaching activities, and each Master student has its own dedicated desk equipped with a dedicated Windows PC to undertake the master thesis. This lab hosts also the activities on the biomechanical cable-driven devices, which can be built and tested freely.

2.2. Vehicles lab

The laboratory of Vehicle Dynamics of DII offers measurement machines designed to characterize different aspects of vehicles. In particular, the Vehicles Lab is equipped with testing facilities for the measurement of the inertia characteristics of 2- and 4- wheeled vehicles and their sub-systems, the analysis of the rider response in 2-wheeled vehicles, and the characterization of the lateral response of tires.

The instrumentation is employed by post-doc researchers, Ph.D. and Master students for research activities, occasionally in collaboration with companies.

The laboratory includes also a Univeristy Student team that participates in the MotoStudent Internaltional Competation. The team, under the name 'QuartoDiLitro', consists of 20-30 students, belonging to different departments of the University of Padua.

2.3. Vibrations and Modal Analysis lab

The laboratories of Modal Analysis and Vibration Mechanics of DII are equipped with instruments and facilities that are relevant to research projects funded by public institutions and companies. The lab is used by post-doc researchers, Ph.D. students and also by Master students.

In particular, the Modal Analysis Lab is equipped with instrumented hammers for impulsive excitation, sensors, and acquisition systems that have been already successfully used for testing robots, light-vehicles components, and for tuning piezoelectric harvesters.

The Vibration Mechanics lab is used to perform different experiments on piezoelectric energy harvesters excited by wind and base excitation. The lab is equipped with piezoelectric shakers of different sizes and it also hosts a small wind tunnel.

3. Main research topics

The research activities carried out by the MMSA research group lie in the definition of advanced modeling of the dynamics of mechanisms and machines, which is fundamental to understanding their kinematics and dynamics and optimize their control. The theoretical analysis is translated into models and simulations, to refine the underlying equations before the experimental validation. The validation and analysis of mechanical systems is one of the key expertise of the MMSA research group, with deep knowledge about modal analysis, in-field dynamic testing of vehicles, mechanism and machines, and robotic work cells. This approach allows the research group to study a wide range of topics, from human-interactive robotics and industrial automation to vehicles and energy harvesting and control.

3.1. Industrial robotics

In the field of industrial robotics, the research group has explored many topics, ranging from collision avoidance techniques for obstacles in the workspace (both fixed obstacles and moving obstacles), trajectory optimizations and analysis of industrial applications.

The research group employs industrial vision systems to identify objects, track movements and validate the proposed models without direct contact with the mechanical systems. Light filters, optics and triggers are adopted.

In the last years the research has focused on exploiting redundancy (both structural and functional) to improve the performance of the industrial setup. Most of the time the target of optimization is the increase of productivity, but other optimization goals (such as energy efficiency or actuators torque) have been studied for specific applications.

The exploitation of the redundancy has been analyzed in two ways:

- Reducing movement time between two locations: since the movement time between two poses depends both on the motion law and on the actuators displacement, the redundancy has been used to reduce at minimum the displacement of the actuators so that the resulting movement time will be reduced (assuming that the same motion law is employed) [1, 2]. The redundancy is applied both for point-to-point motions and for movements that require via-points, such as movements in which obstacles are present in the workspace or movements in which the robot must move from one side to the other of the workpiece [3].
- Reducing the overall takt time: the takt time may depend on the order of the tasks that the robot has to perform. Hence, after the movements between different poses are optimized, the order of the tasks may be optimized as well. The research group has exploited the Travelling Salesman Problem (TSP) to reduce the takt time: the exploitation has been possible thanks to the introduction of some mathematical constraints on the problem so that different robot configurations may be included in the problem, but only a single configuration for each working location will be chosen [4]. At the moment, the research group is exploiting TSP to assign the tasks to two or more resourced without requiring long computational times.

Moreover, novel control strategies are currently being explored. To do so, an old Adept 550 SCARA robot has been modified so that it can be controlled via Beckhoff servo drives (Figure 1:). The simple yet powerful hardware of this robot makes it perfect for the implementation of the control strategies: in fact, the mechanical structure is of very high quality and the Denavit-Hartenberg parameters are provided by the manufacturer, thus the research can focus on the control side of the problem, without worrying about the kinematic aspect.

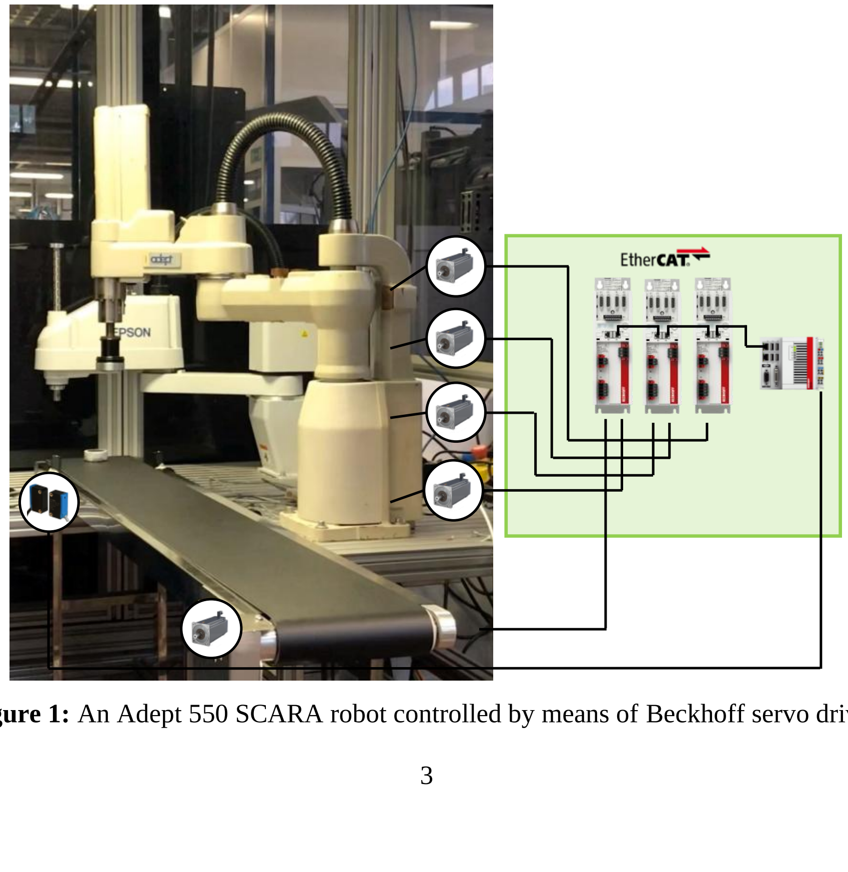

Figure 1: An Adept 550 SCARA robot controlled by means of Beckhoff servo drives.

Finally, mechanisms are employed in many works to perform simple tasks without the requirement of expensive hardware. In particular, the research group has developed a novel feeding system which consists of a rotating feeder that required a single movement for each batch of parts, whereas standard hoppers require two movements for each batch (opening and closure) [5, 6]. The feeding system has been validated, and a patent has been issued.

Another mechanism that has been studied aims at achieving the perpendicularity of the end effector to any inclined surface: robot drilling assumes that the robot is always perpendicular to the surface to be drilled, but it is not always the case, mostly due to defects in the production if the workpiece. This problem is usually tackled by means of control strategies or by using active feedback systems. Instead, the proposed mechanism uses passive springs to align the end effector to the surface. This approach can be used for regular surfaces, such as planar surfaces or curved surfaces with constant curvature.

3.2. Collaborative robotics

Collaborative robotics has been studied from different angles:

- It has been studied the improvement of the performances of the collaborative applications by employing real-time collision avoidance strategies, identifying the tasks to be performed by the robot and how the physical encumbrance of the robot may affect the performance of the operator [7, 8].
- It has been studied the mechanical impact that may occur between robot and operator: the interaction is modeled by means of standard physical models (such as the Hunt-Crossley model) and the maximum forces and pressure are calculated. The interaction is studied both via simulations (Matlab-Simulink models) and via experimental tests between robots and masses. The interaction force is measured by means of load cells.
- Novel end effectors have been developed. The aim of these end-effectors is reduce the interaction force between the robot and the operator, so that the application is more secure, and the robot may move faster, improving the efficiency of the workcell [9].
- In the last two years the “human factors” are introduced in the collaborative research. The human factors (such as, for example, how the operator feels about the movement of the robot) are being investigated [10].

3.3. Vibration of robots

The oscillations of the end effector at the working points may affect both the quality of the final product and the performance of the robot. To tackle this problem, dynamic models of the robot have been developed, in which the compliance of the structure has been included. Preliminary studies have shown that the compliance of standard industrial robots are mainly due to the stiffness of the transmission of the joints. Hence, experimental tests have been performed both on an Adept Viper 650 (a 6-axis robot) and on an Adept Quattro 650h (a 4-axis parallel robot).

The experimental tests on the Viper 650 robot [11] aimed at finding the stiffnesses values of the robot joints, adopting the modal approach: the robot structure was hit via an instrumented hammer in specific robot configurations that allowed only specific joints to be excited. Hence, the stiffness of each joint was identified. The only exceptions were related to joints 2 and 3: since these two joint axes are always parallel, there was no way of exciting a single joint (the two joints are coupled). Hence, the coupling of these joints was studied.

The experimental tests on the Quattro 650h aimed at exploiting the energy harvesting to power sensors or reduce the oscillation along a path. Experimental tests and analysis are currently in development.

3.4. Energy harvesting

Nowadays remote sensors nodes can be fed by means of vibrations energy harvesters that scavenge energy from industrial or natural vibrations or by the action of wind [12], rain [13], or due to the irregularity of the road in light vehicles [14].

The research group focuses on the development, simulation and tuning of efficient piezoelectric harvesters.

The research carried out by the group focused on the modal analysis methods that are used in the field of vibration with the aim of identifying the properties of new materials and tuning devices [15]. The identification was carried out in the frequency domain, because on the one hand the impact force generates a significant excitation in a wide frequency band and on other hand the cantilever harvester is characterized by a well-distinct resonance peak. The measured frequency response function was fitted with a mathematical model that includes the unknown parameters of the material, which are reconstructed by using an optimization process. The proposed method was validated identifying the properties of well-known harvesters. Moreover, piezoelectric properties obtained by applying an impulsive excitation were compared with those obtained by applying a harmonic excitation generated by a shaker.

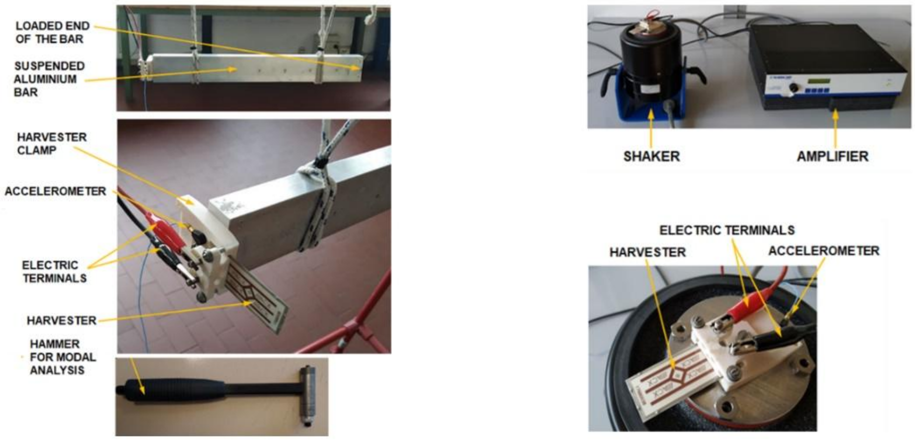

Figure 2: (left) Setup for the identification by means of an impulsive excitation, (right) test rig for harmonic tests.

Moreover, the vibration research group focused also on piezoelectric energy harvesters subjected to road and wind excitation in light vehicles. Previous research showed that the tuning of the harvester to road-excited vibrations requires a low natural frequency that can be achieved by means of a large tip mass. This tip mass can be used to equip the harvester with a bluff body for energy harvesting from wind-excited vibrations. The interaction between the bluff body and the wind flow generates a vortex shedding phenomenon that at a certain wind velocity is able to excite the harvester in resonance condition. Moreover, the turbulence of the incoming wind is able to excite the bluff body in the high velocity range (buffeting excitation).

The research carried out by the group dealt with mathematical and experimental analyses for the development of a hybrid piezoelectric harvester able to scavenge energy from road-excited vibrations and wind. A multi-physical mathematical model that takes into account the couplings between the mechanical, electrical and fluid domains was developed. The coupled equations were implemented and solved in Matlab and were used for the harvester design. Two prototypes were developed and tested. The results of experimental tests carried out in a wind tunnel and in open space showed the potentialities of the proposed harvester layout.

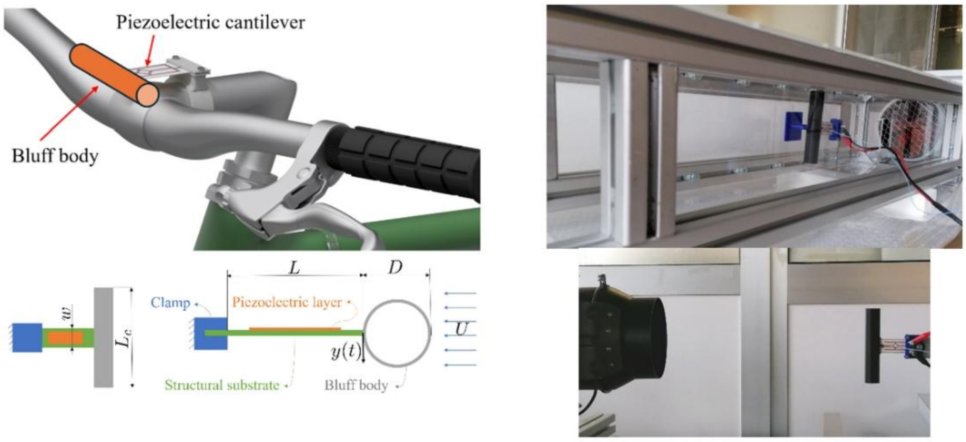

Figure 3: (left) Example of installation of the hybrid harvester and scheme of the harvester, (right) Prototype inside the wind tunnel and in open space tests.

Lastly, the research group also worked on energy harvesting from raindrops. Raindrop energy harvesting through piezoelectric devices offers a promising solution to power small sensors, especially in adverse weather conditions when traditional solar panels are less effective. This part of the research focused on the design of a new cantilever harvester that uses the impact of a drop on a liquid surface created on the harvester in order to improve the conversion from kinetic energy to electric energy. Experimental tests carried out both outdoors and indoors were performed to assess the validity of the proposed design. The phenomena that led to the increased performance of the harvester were analyzed both experimentally, by means of a high-speed camera, and analytically, by means of a mathematical model. The mathematical model developed, which was based on the oscillation of the liquid mass caused by the impact and on the linear momentum equation, is simple and can be used to estimate the measured voltage within a good approximation.

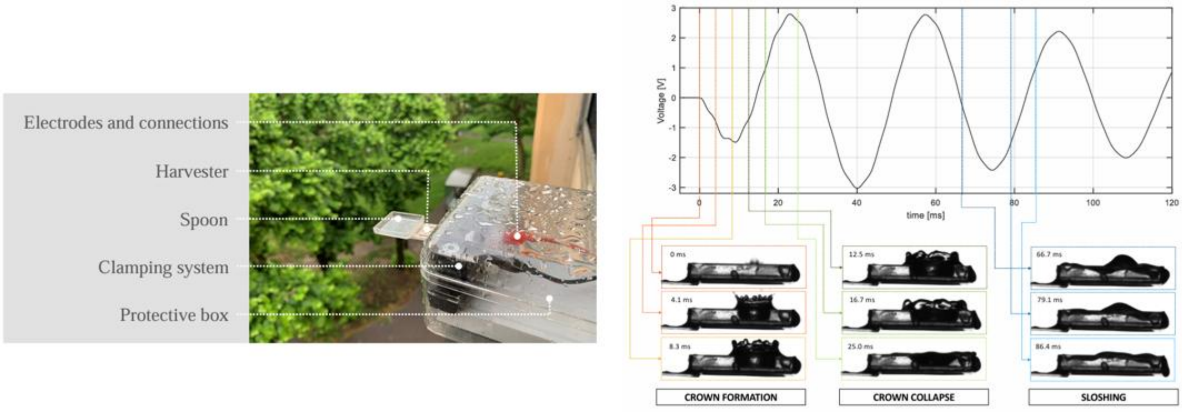

Figure 4: (left) Prototype of the raindrop harvester with spoon in an outdoor test with “empty spoon” (right) Drop impact on a full spoon. Time evolution of voltage and camera pictures at selected instants, showing the main phases of water motion.

3.5. Cable-driven robotics

Cable-driven robots merge the advantages of parallel robots, i.e., placing the majority of its mass on the frame, thus achieving high performance, while featuring a low cost design with a wide workspace [16]. Their characteristics make them suitable for applications in industry, entertainment, and rehabilitation.

In particular, the research group has developed a deep knowledge of the cable failure problem, which is the greatest drawback when working with cable-driven parallel robots, as it is not possible to control the end-effector position, and an emergency procedure may not be successful in stopping the end-effector. Hence, the research group has focused on the definition of appropriate recovery strategies for the end-effector during a cable failure scenario (Figure 5:)Figure 5:, controlling the remaining healthy cables to recover the end-effector. To further improve the system, a cable failure detection and identification strategy has been developed to correctly identify the broken cable and react accordingly, focusing on a sensorless approach to improve its desirability [17].

Figure 5: The Cable-driven robot in the Robotics lab.

Regarding the applications of cable-driven robots in rehabilitation, the research group has developed motion assisting devices which help in the natural motion of the assisted limb. Indeed, the low inertia and high-payload-to-weight ratio of cable driven robots offer advantages to rehabilitation robots. The MaRiBot in Figure 6: is a 5-degrees-of-freedom hybrid robot composed of a rigid planar robot arm (2 DOF) and a payload driven by cables (3 DOF) and controlled by DC motors fixed on the robot links [18]. A different approach is presented by the ASSIST project (Fig. 3b), which has been funded by the Italian PRIN 2022 program, showing the current attention and interest on motion assisting devices, which is in accordance with the progressive aging of the Italian and European population. The design is a 2-DOF CDRR composed of two rings: an upper ring for the placement of the cables' exit points, and a lower ring, placed at the patient's wrist and featuring the attachment points for the cables. By properly controlling the cables it is possible to obtain both the bending/extending motion of the forearm and the prono-supination movement [19].

Figure 6: (left) The MaRiBot. (right) The Cable-driven robot for the rehabilitation of the upper limb.

3.6. Vehicle dynamics

The topic of vehicle dynamics covers both the 2- and 4- wheel vehicles. Such vehicles are modeled and simulated and their trajectories along a track are studied and optimized. The research targets in this area are:

- Modeling and simulation of 2- and 4-wheel vehicles. Phase plane analysis, study of the stability region by means of phase portrait, algorithms for electronic stability control. Techniques for estimating the trim angle of a motor vehicle, on-track testing on prototypes of instrumented full-scale vehicles.
- Optimal vehicle control. Optimization of the minimum time maneuvers for 2 and 4-wheel vehicles. Torque vectoring techniques for the improvement of vehicle dynamics to improve stability and safety, "fun-to-drive", and for maximizing the energy efficiency of multi-engine electric vehicles.
- Hybrid electric vehicles. Feedforward techniques for the energy optimization of multi-engine electric motorcycles. Energy management strategies for hybrid vehicles.
- Experimental identification of characteristics of vehicles. Location of the center of gravity and inertia tensor of vehicles and their sub-systems. Lateral and steering response of riders in 2-wheel vehicles. Tire characterization, including force-slip lateral response, vertical and lateral carcass stiffness, and tire geometry.

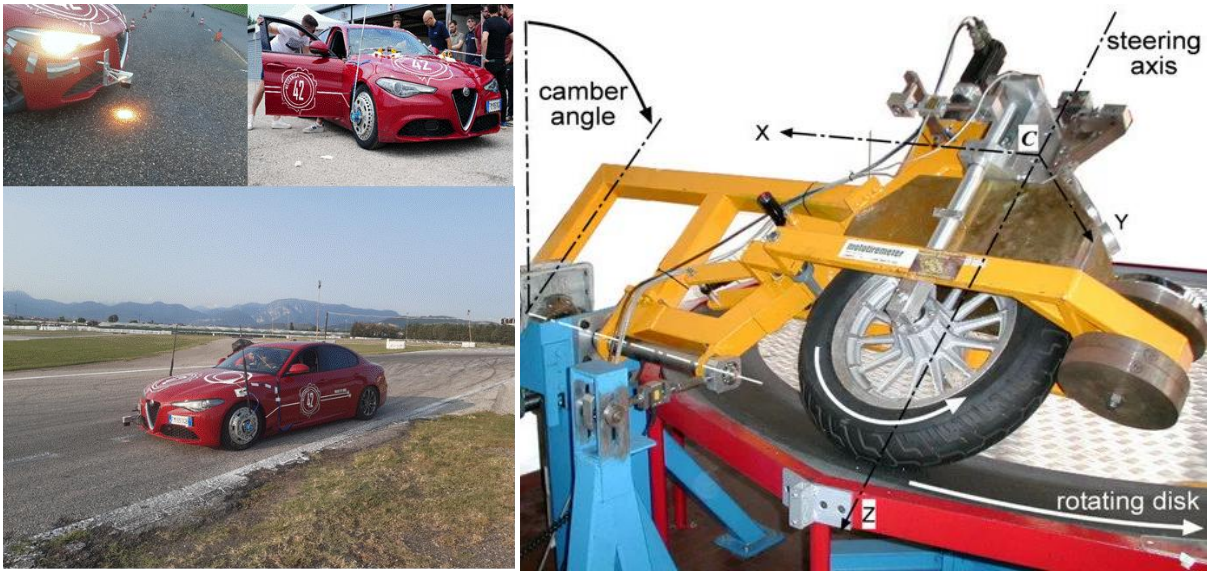

Figure 7: (left) The vehicle used for the optimal vehicle control tests. (right) Tyre test rig for the measurement of tire characteristics.

3.7. Drones

Activities on drones focus on the study, both from simulation and experimental point of view, of new potential applications of these systems in the field of Inspection and Maintenance (I&M) of civil infrastructures.

The research is particularly focused on the modeling, simulation and experimental validation of drones equipped with actuated mechanisms or robotic arms (also known as UAM, Unmanned Aerial Manipulators). The possibilities of these systems in the I&M field can be multiple: placement of sensors at height, accurate tracking of inspection trajectories with cameras, collection of samples in hard-to-reach positions, etc.

Among the theoretical activities carried out:

- Development of a free-flying robotic systems simulator for testing control algorithms and the interaction of the UAM with the environment.
- Development of novel CLIK (Closed-Loop Inverse Kinematics) algorithms for Aerial Manipulators (cit. articoli). These algorithms work at velocity or acceleration level and can be used for a decentralized control of the manipulator that takes into account the movements of the base [20, 21].
- Design and simulation of balanced manipulators attached to drones.

In the laboratory there are two multicopters (DJI S1000 and a custom platform with Tarot T960 frame, in Figure 8) and a Trossen WidowX-250s Mobile robotic arm that will be used to perform experimental tests.

Figure 8: (left) Manipulator used for the UAM (WidowX 250 Mobile arm), (right) Custom UAV platform that will mount the manipulator (Tarot T960 frame).

3.8. Underactuated robotics

The research group has focused on the control of differentially flat underactuated robots. A differentially flat underactuated robot can control the trajectory of the passive joint by means of specific inertial properties and by employing torsional springs on the passive joint.

Starting from the state of the art, the research group has been able to advance the control strategy to perform very fast movements (around 0.6s) without oscillation at the end of the movement. This achievement has been possible thanks to the introduction of the damping in the mathematical model [22], a term that was usually included in the control strategies by means of feedback systems; instead, the experimental setup used for the validation of the model does not employ feedback sensors, and the trajectory of the passive joint is measured via industrial cameras: the video is post-processed only after the movement of the robot and does not provide any feedback to the control strategy.

The model has been improved by also including via-points [23], improving the dexterity of the robot. One or more via-points have been employed, and challenges on the development of the model have been addressed.

The differentially flat theory has been employed both for serial and cable driven robot. For the latter case, a two-dof serial robot is mounted as the end-effector of the cable-driven robot, and the origin and orientation of the first link is controlled by means of cables.

4. Main teaching activities

The teaching activities related to the MMSA group cover both bachelor and master courses. Starting from the more theoretical courses on Applied Mechanics for more than 200 bachelor’s students of Mechanical Engineering and Aerospace Engineering, the group teaches about mechanisms, transmissions and cams.

As for the Master students, the researchers teach courses on Mechanical Vibrations, Vehicle Dynamics, Hybrid and Electric Vehicles, Industrial Robotics, Modelling and Simulation of Mechanical Systems, Actuator Dynamics and Safety of Robotic Systems. All these courses have a focus on the industrial setting and aim at giving the students practical notions to be used outside of academia. This is possible also thanks to the adoption of some laboratories, such as the one of Industrial Robotics, in which the students learn how to program several real industrial robots with real tasks, such as pick up objects on a moving conveyor belt.

5. Conclusions

The mission of the MMSA research group of the University of Padova covers several aspects of the dynamics of mechanical systems, from Robotics to Vibrations, from Vehicles to Drones. Research projects and training programs are offered to bachelor and master students of different degrees and fields.

The current activities have been shown in this paper, which could be used for fostering future collaborations also with foreign research institutions.

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