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Editorial

Special Issue "Advances in Aerial, Space, and Underwater Robotics"

Silvio Cocuzza [1,*], Alberto Doria [1] and Benedetto Allotta [2]

1 Department of Industrial Engineering, University of Padova, 35131 Padova, Italy
2 Department of Industrial Engineering, University of Florence, 4-50121 Firenze, Italy
* Correspondence: silvio.cocuzza@unipd.it

1. Introduction

Free-base robotic systems are extensively used in underwater, air, and space environments. They are employed for inspection and surveillance, assembly, as well as for service tasks in which physical interaction with the environment is present. Common challenges related to sensing, interaction, the control of the platform and of the end effector (if present) must be addressed. In this Special Issue, we present recent advances in the field of aerial robotics (16 papers: 1 review and 15 research papers), space robotics (9 papers), and underwater robotics (7 papers).

2. Aerial Robotics

This Special Issue collects 16 papers in total in the field of aerial robotics, which are divided into 15 research papers and 1 review. The platforms used in these researches are based on a rotary-wing unmanned aerial vehicle (UAV, 9 papers, 3 of them are on aerial manipulation), on a fixed-wing UAV (6 papers), or on a flapping-wing UAV (1 paper).

A consistent set of the papers contained within this Special Issue focuses on the motion planning and control of rotary-wing UAVs (9 papers), either with or without an end-effector to interact with the environment. In particular, three papers home in on the emerging field of aerial manipulation (UAV plus robot manipulator), one paper is a review on the propulsion system design methods of both rotary-wing and fixed-wing UAVs, and all the other works are written on conventional rotary-wing UAVs.

In the field of aerial manipulation, Pasetto et al. [1] propose two novel inverse kinematic control methods, used to track a trajectory and pick a load with an aerial manipulator. Among the main challenges in aerial manipulation, one which has been addressed with this work, is related to the movement of the UAV base caused by manipulator disturbance torques and forces. This is a motion that jeopardizes the precision of the robot manipulator. The first proposed method to be presented is adapted from the generalized Jacobian formulation used in space robotics and includes the change in system momentum resulting from gravity and UAV control forces in the inverse kinematic control equation. To drastically reduce the undesired UAV motion by exploiting the kinematic redundancy of the manipulator, the extended generalized Jacobian is then introduced by adding an additional task constraint that minimizes the reaction torques on the UAV. The proposed methods are suitable for real-time implementation and are validated through dynamic simulations. Nigro et al. [2] propose a motion control scheme for a new concept of omnidirectional UAV for transportation and manipulation tasks. The proposed quadrotor platform can provide multi-directional thrust thanks to an actuated gimbal mechanism in charge of modifying the orientation of the frame on which the four rotors are mounted. The mechanical design outlined above, unlike omnidirectional UAVs with tilted propellers, avoids internal forces and energy dissipation due to non-parallel propellers axes. The proposed motion controller is based on a hierarchical two-loop scheme. The external loop computes the force to be applied to the vehicle and the reference values for the additional

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joints, while the inner loop computes the joint torques and the moment to be applied to the multirotor. Simulation case studies prove the capability of the omnidirectional UAV platform to track a 6-Degrees-of-Freedom (DOFs) trajectory, both in free motion conditions and during a task involving grasping and transportation of an unknown object. Aerial continuum manipulation systems (ACMSs) have been recently introduced via the integration of a continuum robot (CR) into an aerial vehicle to address several issues of conventional aerial manipulation systems. This includes concerns such as safety, dexterity, flexibility and compatibility with objects. The nonlinearity and complexity of CRs modeling make it difficult to design a coupled ACMS dynamic model suitable for practical applications. In this context, Samadikhoshkho et al. [3] present a coupled dynamic model for ACMSs to deal with CR and the aerial vehicle as a unified system. This is based on the Euler–Lagrange formulation. The simulation results of free flight motion scenarios are reported to verify the effectiveness of the proposed modeling and control techniques.

In this Special Issue, several research works concerning conventional rotary-wing UAVs are presented, mainly on dynamics, control, sensor fusion for localization, and motion planning. 3D motion planning algorithms play a vital role in attaining various levels of autonomy for UAVs. Unfortunately, developing these represents a rather complex task, due to the increased dimensionality of space and consideration of dynamical constraints for a feasible trajectory. In particular, in 3D path search problems, it is quite difficult to avoid additional expanded nodes due to increased dimensionality, with various available search options. Farid et al. [4] discuss and implement a modified heuristic-based A * formalism that uses a truncation mechanism in order to eradicate the mentioned problem in the motion planning of a UAV in a 3D obstacle-cluttered environment. The proposed approach significantly reduces the path length and renders only those nodes that are obstacle free. Subsequently, the nodes of the shortened path are used to generate a dynamically feasible and optimal trajectory for the quadrotor UAV. The generated optimal trajectory minimizes the control effort and ensures longer endurance times. The results of the numerical simulations validate the theoretical developments. Park et al. [5] present an efficient global and local real-time trajectory generation method for an autonomous quadrotor UAV to complete a flight mission in a cluttered and unmapped environment. A minimum-snap global path planner generates a global trajectory that comprises some waypoints in a cluttered environment. When facing unexpected obstacles, the method modifies the global trajectory using geometric planning and closed-form formulation for an analytical solution with a 9th-order polynomial. Experiments reveal that the proposed method can provide safer and faster trajectory generation than the numerical method in a real cluttered environment. The complex non-linear dynamic behavior of the proportional integral derivative (PID) controller in quadrotor UAVs requires advanced stabilizing control of their movement. Traditional methods for tuning quadcopter PID, such as Ziegler–Nichols (ZN), do not provide optimal control and might leave the system with potential instability and cause significant damage. One possible approach that alleviates the tough task of nonlinear control design is the use of meta-heuristics that permit appropriate control actions. Sheta et al. [6] present a PID controller tuning that uses meta-heuristic algorithms to stabilize quadcopter movements, such as genetic algorithms (GAs), the crow search algorithm (CSA) and particle swarm optimization (PSO). The simulation results related to quadcopter movement control using PSO present an impressive level of control performance, compared to GA and CSA. Guerrero-Castellanos et al. [7] propose an attitude tracking control design for application to multirotor UAVs, based on an active disturbance rejection capabilities (ADRC) approach. The proposed technique groups the endogenous and exogenous disturbances into a total disturbance, and then this is estimated online via an extended state observer (ESO). Further, a quaternion-based feedback is developed, something which is assisted by a feedforward term obtained via the ESO to relieve the total disturbance actively. The simulation results allow for the validation of the theoretical findings. The use of UAVs in industrial applications and, in particular, in environments with degraded satellite signals is rapidly increasing. In this context, Carrasco et al. [8] present a highly reliable solution for the 3D localization of aerial robots. The proposed solution is based on a probabilistic approach that makes use of a 3D laser scanner, radio sensors, a previously built map of the environment and input odometry, to obtain pose estimations that are computed onboard the aerial platform. Experimental results show the feasibility of this approach in terms of accuracy, robustness and computational efficiency.

A review of the design methods used in defining and sizing the propulsion system of both rotary-wing and fixed-wing UAVs is presented by Amici et al. [9]. Since every design choice strictly affects and is affected by the overall system, the design of the propulsion system for UAVs demands an inclusive multidisciplinary approach from the earliest design phases. In this work, the literature indications and hints are combined into an integrated framework for the functional design of the propulsion system of UAVs. The procedure aims to support the designer in the preliminary selection of the propulsion candidates and the quick sizing of the supply system, especially during the early phases of the design process.

On the other hand, six papers of this Special Issue focus on fixed-wing UAVs, focusing in particular on novel concepts, control methods, motion planning, stabilization methods, sensors for environmental monitoring, and on risk assessment. In the recent years, fully electric aircrafts for the so-called urban air mobility scenario have gained increasing interest. These air taxis, also called electric vertical takeoff and landing (e-VTOL) vehicles, are conceived to exploit vertical takeoff and landing capabilities in order to carry people from one point to another, typically within the same city. In this context, Palaia et al. [10] present a new conceptual design methodology for urban air vehicles and apply it to an innovative convertiplane, called TiltOne, based on a box-wing architecture coupled with tilt-wing mechanisms. Several configurations are designed according to the current regulations imposed by European Union Aviation Safety Agency, and sensitivity analyses are carried out varying the main design parameters, such as wing loading and propellers disk loading, as well as main top-level aircraft requirements. The results provide an overview for the contemporary operational capabilities of such aircraft. In addition, possible scenarios are depicted for a near-future horizon based on the assumption of increased performance levels for the electric powertrain components. Coates et al. [11] present a nonlinear singularity-free autopilot design for multivariable reduced-attitude control of fixed-wing UAVs. The proposed controller design can be used with state-of-the-art guidance systems and is implemented in the open source autopilot ArduPilot for validation through realistic software-in-the-loop simulations. Wang et al. [12] present a virtual force-based guidance law (VFGL) to enhance path both following and obstacle avoidance in unmanned aerial vehicles. First, a virtual spring force and a virtual drag force are designed to follow straight lines; then, the dynamics of the cross-track error is equivalent to a spring mass system, which is easy to tune to acquire stability and non-overshoot convergence. Secondly, an additional virtual centripetal force is designed to counteract the influence of the curvature of the planned path. This enables the guidance law to accurately track a curve with a time-varying curvature. Thirdly, an extra virtual repulsive force is directly designed according to the sensor inputs; the virtual repulsive force pushes the vehicle away to move around obstacles. Both the numerical and hardware-in-the-loop simulation results demonstrate the effectiveness of the proposed guidance law for path following and obstacle avoidance in UAVs. Azouz et al. [13] present the stabilization of a large, unmanned airship hovering above a loading and unloading area. The study concerns a quadrotor flying wing airship. The dynamic model of the airship is presented, and a strategy for controlling it under the effects of a gust of wind is proposed. A feedforward/feedback control law is proposed to stabilize the airship when hovering. As part of the control allocation, the non-linear equations between the control vectors and the response of the airship actuators are highlighted and solved analytically through energy optimization constraints. A comparison is performed with classical numerical algorithms. This demonstrates the power and interest of the proposed analytic algorithm. Lerro et al. [14] perform the safety analysis of an air data system (ADS) based partially on synthetic sensors. The ADS is designed for as part of the small aircraft transportation (SAT) community and is suitable for future

UAVs and urban air mobility applications. The main innovation of the ADS is based on the estimation of the flow angles (angle-of-attack and angle-of-sideslip), using synthetic sensors instead of classical vanes (or sensors). Conversely, pressure and temperature are directly measured with Pitot and temperature probes. As the ADS is a safety-critical system, safety analyses are performed and the results are compared with the safety objectives required by the aircraft integrator. Worldwide, there is a significant increase in the use of UAVs by emergency services, for example in disaster management. They offer extensive possibilities for application in rescue operations. Anyway, to minimize the risks associated with conducting air operations with UAVs, the application of the specific operations risk assessment (SORA) methodology is important. In this context, Janik et al. [15] develop guidelines and directions for adapting SORA to the requirements of the operational work of emergency services. Thus, they present the most important risks related to conducting operations with the use of UAVs by first responders (FRs) and show the sample risk analysis performed for this type of operation.

Finally, one paper of the Special Issue is focused on flapping-wing UAVs and, in particular, on a novel bioinspired system. In this paper, Perez-Sanchez et al. [16] present the development of a novel bio-inspired robotic tail for flapping-wing aerial robots using macro fiber composites (MFC) as actuators. The use of this technology will allow researchers to come closer to approximating the nature of the tail, aiming to mimic a bird tail's behavior. The tail will change its shape, performing morphing and thus providing a new type of actuation methodology in flapping control systems. When compared with traditional actuation approaches, one key advantage given by the use of MFC is their ability to adapt to different flight conditions via geometric tailoring, imitating the flight of birds in nature. Theoretical explanations, design, and experimental validation of the developed concept, undertaken using different methodologies, are presented in this work.

3. Space Robotics

Space robotics is the main topic area of nine papers of this Special Issue. In particular, four papers focus on the development and control of free-base robotic systems, three on novel techniques for the attitude control of satellites, one on the wheel odometry of a planetary rover, and another on the proof of concept of a novel exosuit for space activity.

The typical application of free-base robotic systems in space is the capture of non-cooperative satellites. In particular, Fu et al. [17] propose a repetitive learning sliding mode stabilization control for a flexible-base, flexible-link and flexible-joint space robot for use to capture a satellite, a process which is validated by a series of dynamic simulations. The system is decomposed into slow and fast subsystems using the singular perturbation theory. To ensure that the base attitude and the joints of the slow subsystem reach the desired trajectories, link vibrations are suppressed simultaneously, and a repetitive learning sliding mode controller based on the concept of the virtual force is designed. Moreover, a multilinear optimal controller is proposed for the fast subsystem to suppress the vibrations of the base and joints. Two sub-controllers constitute the repetitive learning sliding mode stabilization control for the system. This ensures that the base attitude and joints of the system reach the desired trajectories in a limited time after capture, obtain better control quality, and suppress the vibrations of base, links and joints. Ai et al. aimed to address the problem that the joints are easily destroyed by the impact torque during the process of space robot on-orbit capture of a non-cooperative spacecraft. As such, a reinforcement learning control algorithm, combined with a compliant mechanism, is proposed by [18] to achieve buffer compliance control. The compliant mechanism absorbs the impact energy through the deformation of its internal spring, and also limits the impact torque to a safe range by combining with the compliance control strategy. The associative search network is employed to approximate unknown nonlinear functions, and an adaptive critic network is utilized to construct the reinforcement signal to tune the associative search network. The numerical simulation shows that the proposed control scheme can reduce the impact torque acting on joints, by 76.6% at maximum and 58.7% at minimum, in the capturing operation phase. Troise et al. [19] present the preliminary analysis of a novel lightweight and deployable soft robotic system for space applications that can easily be contained in a relatively small package to be deployed when required. The main challenges for soft robotic systems are the low force exertion and the control complexity. As such, in this work, a soft manipulator concept with inflatable links is introduced to face these issues. A prototype of the inflatable link is manufactured and statically characterized using a pseudo-rigid body model subject to varying levels of inflation pressure. Moreover, the full robot model and algorithms for the load and pose estimation are presented, and a control strategy, using inverse kinematics and an elastostatic approach, is developed. Experimental results provide input data for the control algorithm, and its validity domain is discussed on the basis of a simulation model. The minimization of energy consumption is also of the utmost importance in space robotics. In this context, Tringali and Cocuzza [20] present a novel inverse kinematics method for redundant manipulator tracking a desired end-effector trajectory, which is suitable for real-time implementation. The proposed method is based on the optimization of the kinetic energy integral on a limited subset of future end-effector path points, making the manipulator joints move in the direction of minimum kinetic energy. In the simulated tests, the proposed method outperforms the classical pseudoinverse-based solution and proves to be able to avoid singularities. Furthermore, it provides a solution very close to the global optimal one with a much lower computational time, which is compatible for real-time implementation.

In the context of attitude control of satellites, Riano-Rios et al. [21] propose a roto-translational control method for a spacecraft in low Earth orbit (LEO) using environmental forces and torques. Relative orbit and adaptive attitude controllers are integrated to perform roto-translational maneuvers for CubeSats equipped with a drag maneuvering device (DMD). The DMD enables the host CubeSat to modulate aerodynamic forces/torques and gravity gradient torque. Adaptive controllers for independent orbital and attitude maneuvers are revisited to account for translational attitude coupling while compensating for uncertainty in parameters such as atmospheric density, drag/lift coefficients, location of the center of mass (CoM) and inertia matrix. A simulation example of an along-track formation maneuver between two CubeSats with simultaneous attitude control, using only environmental forces and torques, is presented to validate the controller. Then, Henninger et al. [22] propose a safety-aware optimal attitude pointing method for low-thrust satellites in geostationary orbit. The aim of the study is to construct a novel geometric and reinforcement learning-based method to determine attitude guidance maneuvers that maintain equipment in safe and operational orientations throughout an attitude maneuver, in particular avoiding pointing sensitive equipment towards the Sun. The attitude trajectory is computed numerically using the geometric framing of Pontryagin's maximum principle, applied to the vehicle kinematics using the global matrix Lie group representation on SO (3), and the angular velocities are shaped using free parameters. The values of these free parameters are determined by a reinforcement learning algorithm to avoid the forbidden areas, while maintaining the pointing in operational areas. The method is applied to a model geosynchronous satellite and demonstrated in a simulation. Finally, Sandu et al. [23] present the development, construction and testing of a new type of solar–thermal propulsion system which can be used for low LEO satellites attitude control. The service duration of an LEO satellite is limited by the amount of cold gas of the propulsion system that they carry onboard. In the case of the new type of solar–thermal propulsion system proposed in this work, the cold gas is first transferred from the main tank in a buffer tank that is placed in the focal line of a concave mirror. After the gas is heated by the focused solar light, it expands by opening the appropriate solenoid valve for the satellite attitude control. In this way, the service duration of LEO satellite on orbit can increase by 2.5 times compared with a classic cold gas propulsion system. The paper also presents the results achieved by carrying out tests for the hot gas propulsion system in a controlled environment.

Gargiulo et al. [24] present a model-based slippage estimation method to enhance planetary rover localization using wheel odometry. An accurate knowledge of the trajectory of rovers is fundamental to accomplishing the scientific goals of planetary exploration missions. This work presents a method to improve rover localization through the processing of wheel odometry (WO) and inertial measurement unit (IMU) data only. By accurately defining the dynamic model of rover wheels and of the terrain, the authors provide a model-based estimate of the wheel slippage to correct the WO measurements. Numerical simulations are carried out to better understand the evolution of the rover trajectory across different terrain types and to determine the benefits of the proposed WO correction method.

Finally, Di Natali et al. [25] present the proof of concept of a quasi-passive resistive exosuit for space activities. Long-term exposure to microgravity, especially during orbital flights, contributes to muscle strength degradation and increases bone density loss. In this work, a quasi-passive exosuit is proposed to provide muscle training using a small, portable, proprioceptive device. The exosuit promotes continuous exercise by resisting the user's motion during routine all-day activity. This study assesses the effectiveness of the resistive exosuit by evaluating its effects on muscular endurance during a terrestrial walking task. The experimental assessment on biceps femoris and vastus lateralis shows a mean increase in muscular activation of about 97.8% during five repetitions of a three min walking task at 3 km/h.

4. Underwater Robotics

In this Special Issue, there are seven papers in total in the domain of underwater robotics. Three of them focus on novel modular/bioinspired concepts, two on sensor/measurement systems, one on control systems, and one on a fault detection system for thrusters.

Concerning novel modular/bioinspired concepts, a modular biomimetic fish-like autonomous underwater vehicle (AUV) known as RoboFish is being developed by Gorma et al. [26]. The aims of these researchers include mimicking propulsion techniques, observed in nature, to provide high thrust efficiency. Additionally, agility will allow the vehicle to navigate its way autonomously around complex underwater structures. AUVs are involved in subsea inspections and measurements for a wide range of marine industries such as offshore wind farms and other underwater infrastructures. Building upon advances in acoustic communications, computer vision, electronics and autonomy technologies, RoboFish aims to provide a solution to such critical inspections. This work introduces the first RoboFish prototype that comprises cost-effective 3D printed modules, joined together with innovative magnetic coupling joints and a modular software framework. Initial testing shows that the preliminary working prototype is functional in terms of watertightness, propulsion, body control and communication using acoustics, with visual localization and mapping capability. An innovative autonomous underwater reconfigurable vehicle (AURV), designed by Topini et al. [27] at the Department of Industrial Engineering of the University of Florence (named as UNIFI DIEF AURV), is capable of efficiently reconfiguring its shape according to the task at hand. In particular, the UNIFI DIEF AURV has two extreme configurations: a slender ("survey") configuration for long navigation tasks, and a stocky ("hovering") configuration designed for challenging goals as intervention operations. In order to observe the several dynamic features for the two different configurations, a novel formulation for the dynamic maneuverability analysis (DMA) of an AURV, adapting Yoshikawa's well-known manipulability theory for robotic arms, is proposed in this work. Fish swimming is a promising source of inspiration for the development of new propulsion systems for AUVs because they outperform conventional propellers in terms of energy efficiency and maneuverability. Bianchi et al. [28] analyze the motion of batoid fishes, a variety which are considered highly efficient by biologists. Their motion is reproduced by different linkage mechanisms, optimized to fit underwater robots. A bioinspired robot mimicking cownose ray locomotion is then designed and built. Numerical analysis of its dynamics allows authors to measure the size of actuators and to estimate the robot behavior. Finally, the control algorithm that maintains the mechanism synchronization according to different strategies is described and some experimental results are presented.

In the context of the development of novel sensor/measurement systems, Lin et al. [29] propose a robust flow field signal estimation method for flow sensing by underwater robots. Fishes can sense the complex underwater environment by their lateral line system, whereas the flow field is difficult to evaluate using underwater robots. In order to reveal the fish flow sensing mechanism, a robust nonlinear signal estimation method, based on the Volterra series model with the Kautz kernel function. is provided. This is named KKF-VSM. The flow field signal around a square target is used as the original signal. The sinusoidal noise and the signal around a triangular obstacle are considered undesired signals, and the predicting performance of KKF-VSM is analyzed after introducing them locally in the original signals. This method can provide a reference for the application of the artificial lateral line system on underwater robots, improving its adaptability in complex environments on the basis of flow field information. Many software systems run on long-lifespan platforms that operate in diverse and dynamic environments. If these software systems could automatically adapt to hardware changes, it would significantly reduce the maintenance cost and enable rapid upgrades. Shi et al. [30] study the problem of how to automatically adapt to sensor changes, as an important step towards building such long-lived survivable software systems. The proposed approach reconstructs sensor values of replaced sensors by preserving distributions of sensor values before and after the sensor change, thereby not warranting a change in higher-layer software. Experiments on weather data and unmanned undersea vehicle (UUV) data demonstrate that the proposed approach can automatically adapt to sensor changes with 5.7% higher accuracy compared to baseline methods.

In the framework of the development of novel control systems, Muñoz et al. [31] present a dynamic neural network-based adaptive tracking control method for an AUV subject to modeling and parametric uncertainties. The research presents a way to improve the autonomous maneuvering capability of an AUV to perform trajectory tracking tasks in a disturbed underwater environment. This study considers four second-order input-affine nonlinear equations for the translational (x,y,z) and rotational (heading) dynamics of a real AUV subject to hydrodynamic parameter uncertainties, unknown damping dynamics, and external disturbances. The authors propose an identification–control scheme named Dynamic Neural Control System (DNCS) as a combination of an adaptive neural controller, based on nonparametric identification of the effect of unknown dynamics and external disturbances, and on the parametric estimation of the added mass-dependent input gain. Several numerical simulations validate the satisfactory performance of the proposed DNCS tracking reference trajectories in comparison with a conventional feedback controller with no adaptive compensation.

Finally, concerning fault detection systems, Xu et al. [32] present a novel online learning-based fault detection system, designed for underwater robotic thruster health monitoring. In the fault detection algorithm, the authors build a mathematical model between the control variable and the propeller speed by fitting collected online work status data to the model. To improve the accuracy of online modeling, a multi-center PSO algorithm with memory ability is utilized to optimize the model parameters. During the operation, the propeller speed of the underwater robot is predicted through the use of online learning-based model, and the model residuals are used for thruster health monitoring. To avoid false alarms, an adaptive fault detection strategy is established based on the online model update mechanism. The proposed method is extensively validated using different underwater robots, through a sea trial data simulation, a pool test fault detection experiment and a sea trial fault detection experiment.

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