Aerial Field Robotics

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Synonyms

Aerial Field Robotics
Micro Aerial Vehicles in the Field
Unmanned Aerial Vehicles in the Field

Definitions

Aerial field robotics research represents the domain of study that aims to equip unmanned aerial vehicles—and as it pertains to this chapter, specifically Micro Aerial Vehicles (MAVs)—with the ability to operate in real-life environments that present challenges to safe navigation. We present the key elements of autonomy for MAVs that are resilient to collisions and sensing degradation, while operating under constrained computational resources. We overview aspects of the state of the art, outline bottlenecks to resilient navigation autonomy, and overview the field-readiness of MAVs. We conclude with notable contributions and discuss considerations for future research that are essential for resilience in aerial robotics.

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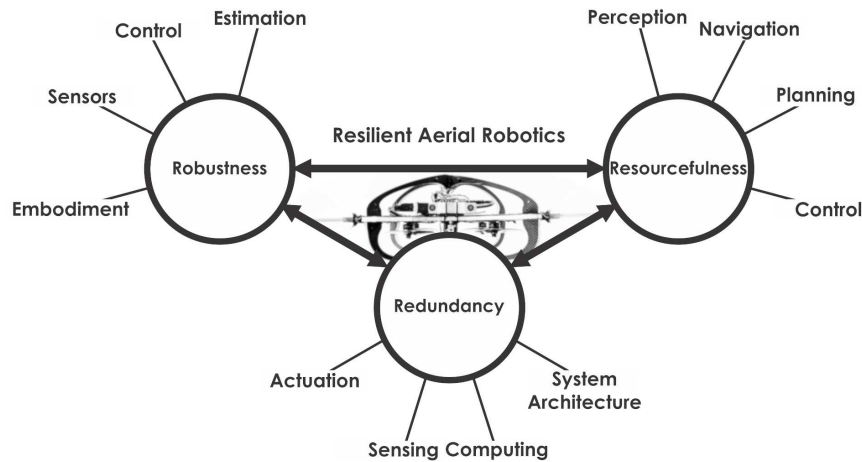Carnegie Mellon University e-mail: `basti@andrew.cmu.edu`

Fig. 1 Core elements of resilient autonomy for aerial field robotics.

Overview

The state of the art in aerial robotics can accomplish impressive tasks. Yet wider use and adoption of MAVs for effective field deployment is limited by the resilience of the components of autonomy. In this chapter, we view each element of the autonomy system under the framework of resilience and examine the latest developments, as well as open questions.

Towards a principled understanding of progress in resilient and field-hardened aerial robotic autonomy, we define resilience motivated by analogous studies in the domain of risk analysis (Howell 2013). A system presents the virtue of resilience if it demonstrates the essential characteristics of a) robustness, b) redundancy, and c) resourcefulness as they relate to its control, perception, path planning, and decision-making. This organization is illustrated in Figure 1.

Robustness incorporates the concept of reliability and refers to the ability of the robot to absorb and withstand disturbances and deteriorating effects of unpredictable situations.

Redundancy involves a robot's capacity and the presence of back-up systems to enable the maintenance of core functionality in the event of disturbances and failures by incorporating a diversity of overlapping subsystems, methods, policies, and last-resort safety schemes.

Resourcefulness refers to the ability to adapt to changes, uncertainties and crises, with the robot's inherent flexibility to deliver a certain functionality using a multitude of possible solutions. This is obtained through the combination of various subsystems that exploit their elementary capacities in different ways to reduce the likelihood of a full failure.

Given this perspective on resilient autonomy, in this chapter, we focus on MAV embodiment, control, perception, and planning in cluttered perceptually-degraded
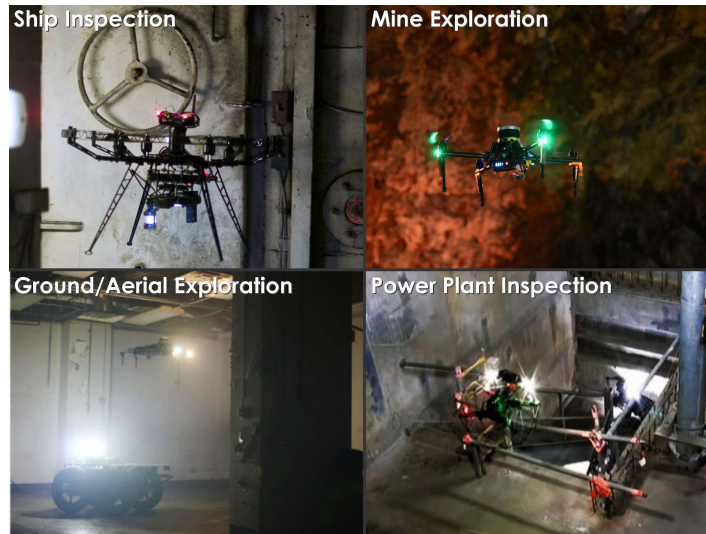
Fig. 2 Examples of MAV field deployments for inspection and exploration in geometrically-complex sensor-degraded environments.

environments (Figure 2). Other aerial robot configurations (e.g., fixed-wing systems) or operational settings are beyond the scope of this study. We survey the state of the art, example applications as reflected in pioneering field results, and seek to identify the open problems and bottlenecks to autonomy.

Key Research Findings

Resilient Embodiment

The mechatronic design of MAVs can contribute to achieving resilient operation and may mitigate limitations and risks to the autonomy stack. We focus on two types of aerial robot embodiment designs, namely collision-tolerant systems and shape-reconfigurable designs. This narrow scope reflects the importance of mitigating the effects of collisions.

When tasked with navigating cluttered and narrow environments, ensuring safe traversal becomes a task of increasing complexity, as any error in localization, mapping, planning or trajectory tracking can lead to a collision. Typically, collisions are seen as catastrophic events and are reasons for mission interruption. However, drawing inspiration from nature, we can identify an alternative, which is to render collisions (within bounds) acceptable.

Fig. 3 Example of a collision-tolerant aerial robot: The Gagarin system (Dharmadhikari et al 2020a) tested in subterranean environments.

The community has developed MAVs that can survive collisions, with an example shown in Figure 3. This can be achieved by developing rigid collision-tolerant outer frames that distribute the impact of a collision along the robot body to prevent localized damage (Briod et al 2014). Other approaches focus on designing soft compliant structural components that cushion the robot from impact. (Klaptocz et al 2013) utilize an Euler spring collision cage, while (Mintchev et al 2017) realize an insect-inspired compliant design protecting the main "core" with the robot electronics and sensors. Emphasizing the protection of the essential parts, (Salaan et al 2019) implement separate rotating shells around each of the quadrotor's propellers. For protecting the robot when it is close to obstacles, (Hedayati et al 2020) present an actuated mechanism that drives an expandable scissor structure. Motivated by origami, (Shu and Chirarattananon 2019) present a passive foldable airframe that acts as a protective mechanism for small multirotors. Emphasizing both compliance and the ability to re-orient in case of a crash, (Zha et al 2020) present tensegrity-based soft collision-tolerant MAVs.

In addition to collision-tolerance, some works show promising results in actively or passively morphing the robot's shape to enter otherwise inaccessible regions. (Falanga et al 2019) develop a quadrotor with independently rotating arms around the central frame. (Bucki and Mueller 2019) modify the design of an MAV replacing the rigid connections between the arms and the "core" with spring hinges that fold the arms downward on low thrusts. The thrust of the robot is controlled such that it allows the arms to fold, and the robot can thus traverse narrow gaps.

Resilient Control

Control for MAVs such as quadrotors and other small rotorcraft is an essential component necessary for their stability and the efficient rejection of disturbances. In this domain, a set of high-performing and robust methods have been presented.

Generally, due to the fact that the MAV attitude dynamics present much smaller time constants compared to their position dynamics, cascade control is commonly employed (Mahony et al 2012), either considering linearized or non-linear dynamics. Different control schemes have been applied, including fixed-gains control (Bouabdallah and Siegwart 2007), possibly using error functions on SO(3)/SE(3) (Lee et al 2010), model predictive control (Kamel et al 2017), geometric $\mathcal{L}1$ control (Kotaru et al 2020), $\mathcal{H}_\infty$ control (Raffo et al 2008), and reinforcement learning (Hwangbo et al 2017). (Powers et al 2013) address the modelling of the systems to account for disturbances such as winds, gusts or those arising due to proximity, while (McKinnon and Schoellig 2016) propose methods to estimate such disturbances. (Hentzen et al 2019) compare the performance of methods to reject these disturbances. Finally, systems with a higher number of actuators have been designed (Kamel et al 2018), and the intrinsic redundancy against propeller failure has been studied (Mueller and D'Andrea 2014).

Resilient Perception

Control and decision-making depend on perceiving the robot's location and understanding the world surrounding it. For MAVs it is essential that the sensors and algorithms are robust and complementary to overcome obscurants and lack of image or geometric texture, while still being able to run efficiently onboard. The architecture of currently fielded systems relies on always-available, sufficiently accurate, low noise, and high-frequency pose estimates to enable navigation and stable flight. While some initial research has explored different paradigms to relax the requirement on estimates, current research has shown significant progress on robust state estimation and 3D mapping that can separate obscurants from thin obstacles. To maximize resilience, robots need resourceful multi-modal approaches that can penetrate all conditions of perceptual degradation and scale across environment sizes.

Navigation in Perceptually-degraded Environments

Researchers have contributed a set of strategies for consistent estimation and autonomous flight using sensors such as LiDARs, cameras, and thermal vision combined with Inertial Measurement Units (IMU). Monocular and stereo visual-inertial SLAM achieves impressive results (Delmerico and Scaramuzza 2018; Rosinol et al 2020) but can get degraded in dark, textureless, or obscurant-filled settings. LiDAR-based methods present particularly robust results (Zhang and Singh 2014) but can

get degenerate within self-similar geometries (Zhang et al 2016) or environments subject to dense clouds of dust and other obscurants. To deal with certain types of obscurants at the cost of less sharp and more noisy images, some researchers investigated LongWave InfraRed (LWIR) thermal vision-based odometry (Khattak et al 2019; Delaune et al 2019). Furthermore, aerial robots often have to deal with varying conditions of perceptual degradation (Figure 4) leading to deprived sensor quality that can render sensor streams uninformative.

Fig. 4 Prominent cases of perceptual degradation and some relevant examples.

In response, (Shen et al 2014) proposed the fusion of multiple heterogeneous sensors and used an Unscented Kalman Filter to provide smooth, globally consistent estimates. Focusing on resilient localization against multiple cases of degradation, the community has focused on multi-modal sensor fusion tailored to computationally constrained MAVs. CompSLAM (Khattak et al 2020) fuses LiDAR, visual cameras, thermal cameras, and inertial cues to resourcefully estimate the robot pose and the map of its surroundings with resilience against the discussed cases of degradation. It relies on a cascaded combination of visual/thermal-inertial fusion and LiDAR Odometry and Mapping motivated by (Bloesch et al 2015; Zhang and Singh 2014). Essential to its design is the observation that if we can identify when a certain estimate, driven from vision or LiDAR, is healthy or not, then a loosely-coupled approach can be effective. LOCUS (Palieri et al 2021) focuses on multi-sensor LiDAR-centric

odometry and mapping with the aim to be deployable across ground and flying robots. It relies on multi-stage scan matching equipped with a health-aware sensor integration module towards seamless fusion of additional sensors. (Ebadi et al 2020) propose LAMP, a pipeline for exploration in perceptually-degraded environments relying on the complementary fusion of diverse modalities including LiDAR and vision. Overall, while prior research was able to integrate redundant sensing modalities current research focuses on how multi-modality contributes to solution quality and on how to detect partial degradation.

Another idea has been to explore learning-based approaches to overcome corner cases that hand-engineered algorithms cannot overcome. Examples of methods trying to increase robustness via learning are TartanVO (Wang et al 2020), CubeSLAM (Yang and Scherer 2019), and ESP-VO (Wang et al 2018). Very recent efforts demonstrate the qualities of combined learning-based navigation methods and visual-inertial estimation (Loquercio et al 2021).

Map Representation

Sensors in the real-world are imperfect and generate systematic and random errors due to the sensor itself, as well as degradation in the environment. These errors can be captured in a sensor model and are typically filtered using Bayesian filtering. These sensor models are then used to update representations for perception. While continuous representations such as Gaussian processes (Tabib et al 2019) have been used, regular volumetric discretization in evidence/occupancy grids is a fast and often sufficiently robust method. Octomap (Hornung et al 2013) is a popular framework that uses octrees to store occupancy information of the environment. However, octrees have complexity of $O(logn)$ for insertion and look-up, where n is the tree depth, rendering building and querying the map in large environments inefficient. Recent works including (Oleynikova et al 2017) utilize voxel hashing for fast $O(1)$ lookups of voxel information from 3D coordinates. This allows incrementally constructing Euclidean Signed Distance Fields maps from Truncated Signed Distance Fields (TSDF). (Whelan et al 2012) used a TSDF with a cyclical buffer, while OpenVDB (Museth 2013) uses a hierarchical data structure offering effectively infinite 3D index space, exploits spatial coherency of time-varying data, imposes no topology restrictions, and supports $O(1)$ random access. Notably, in the above we have considered the common practice of assuming that the state estimate mean is correct. New research considers the role of noise and non globally-consistent estimation (Doherty et al 2019; Cieslewski et al 2019).

Difficult to Detect & Avoid Obstacles

When trying to perceive objects within the surrounding environment, certain factors can render objects hard-to-detect including their size, shape, material type, or coating which can lead to inaccurate maps and potential collisions.

The small cross-section of poles and wires gives a weak signal for both cameras and radars. (Madaan et al 2017) use Convolutional Neural Networks (CNN) to detect wires in monocular images and used synthetic data to train the model. (Stambler et al 2019) also use a CNN and methods for tracking the wires in 3D. Trained purely on real-world datasets, the model outperformed the previous methods on precision and computation time.

Detecting reflective and transparent objects is also a challenge. (Dubey et al 2018) use a CNN to segment thin obstacles (i.e., wire pixels). Another method of detecting transparent objects uses a laser rangefinder and looks for the spike in reflected light as the incident angle approaches the surface normal of the transparent object (Wang and Wang 2017), relying on the laser being able to hit the object near its surface normal.

Resilient Planning

The challenge of resilient aerial robotic autonomy in the field depends upon their capacity to resourcefully plan actions that robustly optimize the robot's mission objectives ("extrinsic goals") and simultaneously ensure the health and safety of the robot ("intrinsic motivations").

Problem Definition

The overall problem considered relates to that of *iteratively* identifying admissible paths that optimize a given set of objectives that may represent extrinsic mission goals (e.g., to search an area) or intrinsic motivations (e.g., to reduce localization uncertainty) given a sequence of online acquired observations of the environment. An admissible path is one that ensures the safety of the vehicle (e.g., guarantees collision-avoidance), and accounts for limitations of the platform.

Path Planning for Aerial Field Robotics

Below we present selected literature and path planning architectures for a class of problems involving diverse objectives.

Path Search

The prime approach to enable path planning for aerial robots involves the (online) reconstruction of a map of the scene. Provided a map, the planning architecture employs a policy for searching admissible paths that optimizes specified objectives for the robot.

Planning to known destinations: In the simplest case, the goal is to arrive at a pre-defined location by avoiding obstacles on the way. The prevailing methods in the literature involve sampling-based path planners that sample in the robot's configuration space (Karaman and Frazzoli 2011) or the control space (Liu 2018). Focusing on computational speed, SPARTAN (Cover et al 2013) creates a sparse graph from vertices that lie on the surface of the collision space, where the optimal path between any two states is shown to be approximately tangential to the surface of the (disjoint) collision sub-spaces. Beyond such techniques, recent efforts on geometric trajectory optimization have shown exciting results on agile navigation given a priori map knowledge (Wang et al 2021).

Planning to optimize extrinsic mission objectives: Beyond the case where the goal destination is known, planning for aerial robotics has extended to include strategies that satisfy more complex mission objectives. Exploration of unknown environments is an example of an extrinsic objective of particular interest, especially as unknown environments may present unforeseen obstacles, involve cluttered regions, hazardous operating conditions, multi-storeyed and multi-branching topologies. To address the challenge, researchers have investigated a range of approaches including frontier-based exploration, sampling-based methods, as well as learning-based techniques.

In the first case, the general approach includes the identification of frontiers and respective configurations towards which the robot is guided given a method for collision-free motion planning. (Nuske et al 2015) present a goal-point extraction strategy for river exploration that maximizes the information gained in the MAV mission by introducing multivariate cost maps. Fast frontier-based exploration is achieved in (Dai et al 2020) exploiting implicit frontier voxels grouping and planning of next viewpoints based on map entropy and travel time derivations.

Sampling-based path search is investigated to identify admissible paths which are also evaluated in terms of information gain. (Bircher et al 2016) proposed the use of rapidly-exploring random trees RRTs to search for collision-free paths and assess a volumetric exploration gain along each of the tree branches. This method, extracts the best path, and commands the robot to go to its first vertex. This procedure is then repeated in a receding horizon fashion. (Dang et al 2020) focused on large-scale and possibly narrow subterranean environments, and proposed a bifurcated architecture of dense local and sparse global graph search. Motivated by this method but focusing on combined exploration and coverage, (Dharmadhikari et al 2020b) employs a multi-hypothesis approach for multi-objective optimization. Since sampling-based methods relying on information gain formulations present the pitfall of being stuck in a local region and do not reach global coverage, (Schmid et al 2020) proposed an RRT*-inspired planner that expands a single tree of candidate trajectories and uses a novel reconstruction gain and cost formulation that allows to perform global coverage and minimize path cost in the global context using a single objective function.

Additionally, learning-based path planning policies have emerged and encompass the possibility to outperform the state of the art. Focusing specifically on subterranean environments, (Reinhart et al 2020) propose a supervised learning agent for autonomous exploration using only point cloud data. (Jung et al 2018) contribute a perception, guidance and navigation system for indoor autonomous drone racing.

Exploiting the ability to learn visuomotor policies, (Bonatti et al 2019) present navigation for drone racing using cross-modal representations. Focusing on following cluttered forest trails with an MAV equipped with a single camera, (Giusti et al 2015) contribute a deep neural network-based image classifier to output the trail's primary direction. (Loquercio et al 2018) contribute DroNet, a CNN trained on driving/bicycle data tuned to guide an MAV flying inside cities.

Co-optimization of intrinsic objectives: By "intrinsic motivations" we refer to all those objectives that do not relate directly to the specified mission but relate to the robot's safety and thus its ability to execute its mission reliably. The case of belief-space planning accounting for state estimation uncertainty *(e.g., due to perceptual degradation)* is of particular interest. (Achtelik et al 2014) propose to employ Rapidly exploring Random Belief Trees (RRBTs) to identify paths that lead to a waypoint, while inherently avoiding motion in unobservable modes. Focusing on autonomous exploration, (Papachristos et al 2017) propose a two-step scheme to first identify an exploration path and then derive refined paths to the first viewpoint minimizing the anticipated localization uncertainty. Perception-aware model predictive control (Falanga et al 2018) unifies control and planning to optimize perception objectives to ensure reliable sensing. These works share similarities with a broader contribution on perception-aware planning (Costante et al 2016). To enable smooth and fast traversal of tightly constrained environments, trajectory generation and optimization algorithms attempt to minimize kinodynamic objectives (Mellinger and Kumar 2011), allowing fast replanning Zhou et al (2019), and risk-aware trajectory refinement to avoid unseen obstacles (Zhou et al 2020).

Examples of Application

With an ever-increasing need to deploy reliable and robust robots in the field, there has been a strong push for developing autonomous aerial robots for challenging environments. We present a selected set among notable achievements that have been realized in this domain and further discuss challenges and bottlenecks to resilient autonomy. We first focus on four selected open competitions that have helped to accelerate research towards resilient and field-hardened aerial robotic autonomy, namely a) the DARPA Subterranean (SubT) Challenge, b) the DARPA Fast Lightweight Autonomy (FLA), c) the Mohamed Bin Zayed International Robotics Challenge(s) (MBZIRC), and d) the Lockheed Martin AlphaPilot Innovation Challenge. The results from such competitions are significant as teams do not have the safety net of repeating an experiment multiple times or in a controlled manner. A set of notable MAV demonstrations, the platforms and hardware used, and significant milestones are detailed in (Table 1).

The DARPA SubT Challenge called for teams to deploy a robotic system-of-systems capable of autonomously exploring diverse underground environments (e.g., mines, metropolitan subterranean infrastructure, caves), detecting objects of interest and correctly reporting their location, alongside broadly mapping such environments.

TEAM	PLATFORM	SENSING	MILESTONE IN MAVs
DARPA Subterranean Challenge			
Explorer	Collision tolerant quadrotor	3D LiDAR, stereo cameras	Marsupial deployment of collision tolerant MAV. Use of topological maps to direct exploration steps (Scherer et al 2021).
CSIRO	Aeronavics NAVI	3D rotating LiDAR payload, gimbal mounted camera	Marsupial deployment of MAV. Navigation through vertical shaft. Explore and Sync strategy for periodic network connectivity (Williams et al 2020).
CERBERUS	DJI-M100, Collision tolerant quadrotors	3D LiDAR, camera, thermal vision, IMU	Autonomous negotiation of staircases. Collision tolerant MAV. Path refinement for safer traversal (Dang et al 2020).
CTU-CRAS-NORLAB	Custom Quadrotor	3D LiDAR, stereo and RGB cameras	Autonomous operation without operator interference. 25min flight time(Rouček et al 2020).
NCTU	Custom Blimp	Stereo camera, IR sensor	Lightweight, collision-tolerant platform. Upto 90 min flight time (Huang et al 2019).
DARPA Fast Lightweight Autonomy Program (FLA)			
SSCI-AeroViron-ment	DJI-F450	Camera, IMU	Steering field controller for obstacle avoidance. Visual-inertial navigation system using monocular camera. Speeds upto 19.0m/s (Escobar-Alvarez et al 2018).
UPenn	DJI-F450	2D nodding LiDAR, stereo cameras, IMU	Autonomous navigation through indoor stairwells. Novel stereo-VIO. Speeds upto 18m/s (Mohta et al 2018; Mohta et al 2018).
MIT-DRAPER	DJI-F450	Stereo cameras	Aggressive flight in urban environments. Use of minimum-jerk trajectories. Speeds upto 9.4m/s (Ryll et al 2019).
AlphaPilot			
UZH-RPG	Standardized quadrotor	Stereo cameras, IMU, laser rangefinder	Simultaneous detection of multiple gates for drift compensation. Speeds upto 8.0m/s (Foehn et al 2020).
TU Delft-MAVlab	Custom-72g quadrotor	JeVois smart camera	Lightweight snake-gate detection. Visual model-predictive localisation (Li 2020).

Table 1 Selected competitions and events.

The Final Event of the competition took place in 2021 and required teams to deploy robots to navigate a large, multi-branching environment, involving both narrow and wide cross-sections, cluttered spaces, and dynamic obstacles in GPS-denied and visually-degraded conditions. Team CERBERUS (Tranzatto et al 2021) won first place and - like other teams (Agha et al 2021) - developed custom collision-tolerant flying platforms capable of autonomous navigation through such adverse environments to perform exploration and search missions. Collision-tolerance and sensing multi-modality were essential for the deployability of MAVs underground. Multiple teams used ground robots to carry and deploy the MAVs inside the environment in a "marsupial" fashion. While almost all the participating teams used aerial robots, they did not evolve to become their primary platform of choice, except for Team

Explorer which scored one-third of their points with aerial robots, highlighting the limitations in endurance and computational capabilities.

The DARPA FLA program aimed to explore non-traditional perception and autonomy to enable high-speed MAV navigation in cluttered environments. The program specifically aimed for autonomous, GPS-denied, fast navigation. The challenges included flying at increased speeds between multi-story buildings, through tight alleyways and narrow openings, into buildings, searching rooms and creating 3D maps of the interior. The challenge was particularly interesting as it led to the development of robust and lightweight estimation, planning, and control approaches for computationally constrained platforms. A stereo Multi-State Constraint Kalman Filter was used by the UPenn's team to provide computationally efficient and robust odometry estimation (Sun et al 2018) achieving fast flight (of 17.5m/s). The MIT-DRAPER team used a closed-form trajectory generation to obtain minimum-jerk trajectories supporting accurate visual-inertial odometry, with the robot speeds planned based on obstacle densities (Ryll et al 2019). The SSCI-AeroVironment team used a monocular camera to navigate the cluttered environment at high speeds (Escobar-Alvarez et al 2018), using the expansion rate of objects in the field of view, a steering-field controller followed an instantaneous steering direction that minimized the risk of collision.

The AlphaPilot competition, organized by Lockheed Martin and the Drone Racing League, challenged teams to develop AI-enabled frameworks that could navigate a fully autonomous aerial robot through complex, multi-dimensional racing courses without any pre-programming or human intervention. The competition focused on pushing the capabilities of vision-based navigation at high-speeds with limited computation available. The final race took place in Texas with MAVLab winning the competition, while the second team - UZH Robotics & Perception Group - was only 3 seconds slower. The MAVLab team deployed a learning-based visual-odometry system (Li 2020) which allowed for a high update rate and thus high-speed flight. Despite this outstanding result, the capabilities of autonomous MAVs are not yet on par with expert human pilots and there is a push to surpass the high speeds and agility demonstrated by the humans (Wang et al 2021).

The MBZIRC is a series of competition events. The MBZIRC2020 consisted of three challenges and a triathlon-like Grand Challenge. In the first challenge, a team of aerial robots was tasked to track and interact with a set of objects autonomously (e.g., an intruder MAV) following 3D trajectories in an indoor setting. In the second challenge, a team of aerial and ground robots was tasked to collaborate to locate, pick, transport and assemble different types of brick-shaped objects to build predefined structures outdoors. In the third challenge, a team of aerial and ground robots was tasked to autonomously extinguish a series of simulated fires in a high-rise building. In the Grand Challenge, the mission task required a team of 3 MAVs and 1 ground robot to compete in a triathlon combining the three previous events. The overall need for robot team coordination, accurate navigation and precise control pushed the frontier of resilience in multi-robot systems and MAVs. The top-scoring team in the Grand Challenge consisted of members from Czech Technical University in Prague, University of Pennsylvania, and New York University.

Beyond the above results demonstrated in the context of the highlighted competitions, the community has reached critical milestones in the domains of robust perception, planning and mapping for long-term deployment of MAVs. Below we discuss achievements in the following directions: a) Autonomy in Extreme Environments, b) High-speed Navigation, c) Multi-Robot Teaming and d) Unconventional Applications of Aerial Robots.

Autonomy in Extreme Environments: Focusing on field tests conducted within extreme indoor or highly cluttered outdoor settings, (Goel et al 2021) details a multi-robot distributed mapping approach for rapid exploration in reduced bandwidth scenarios using a team of aerial robots. (Yang et al 2021) demonstrates topological exploration in large-scale 3D underground settings. Aiming to facilitate efficiency against topologically complex underground environments, (Mansouri et al 2019) proposes visual subterranean junction recognition for MAVs using CNNs.

High-speed Navigation: At higher flight speeds, the simplistic models become increasingly inaccurate as the aerodynamic drag becomes significant and must be considered into the quadrotor's dynamic model. (Rigter et al 2019) demonstrate accurate trajectory tracking for high speed flight inside cluttered indoor environments using compensation for aerodynamic drag. (Zhang et al 2019) reach flight speed of upto 10 m/s using a trajectory library generated offline and evaluated online to check for collisions, and performing probability propagation to determine the path reaching the goal position. Focusing on agility of navigation, (Morrell et al 2018) exploit a significant body of literature for agile MAVs and demonstrate the benefits of differential flatness transformations for aggressive maneuvers incorporating inverted flight.

Unconventional Applications of Aerial Robots: MAVs have pioneered their way to be integrated in a multitude of application domains including industrial inspection and search and rescue. The AeroARMS Project (Ollero et al 2018) was aimed at developing robot designs for grabbing and flying with payload, performing inspection tasks based on vision and control feedback. (Ollero et al 2021) discuss the current status and future research for aerial manipulation. The MultiDrone Project (Alcántara et al 2021) aimed to use multiple autonomous MAVs for media production, demonstrating the use of aerial robots to perform coordinated camera motion. In addition, (Bonatti et al 2020) develops an approach for a single robot to execute artistically selected, occlusion free shots. (Kamel et al 2018) developed an omnidirectional MAV with recent activities focusing on industrial contact-based inspection.

Future Directions for Research

Concluding this chapter, we proceed to identify selected open research problems prohibiting the wider and increasingly effective and resilient field deployment of aerial robotics. For robot embodiment, persistent limitations are related to endurance, safe contact, and robust physical interaction, without the need for heavy designs that de-

grade flight performance. Control for high performance free-flight is largely achieved, but robust and seamless physical interaction is far from established. Perception and planning are two large open research areas for autonomy. While significant progress has been made to allow the robots to estimate their state in environments with dust, or obscurants, true resilience against perceptual degradation is yet to be mastered. With robots venturing into dynamic settings, and operating in environments with thin objects, robust perception remains a key challenge. Simultaneously, the use of dense map-based representations prevents scalability and accordingly selectively sparse, map-free representations or other means are possibly needed for long-term navigation. Even with an accurate and dense map reconstruction, challenges in path planning lead to limitations. Three major constraints relate to the computational costs of planning in complex large-scale but confined worlds as highlighted by the DARPA Subterranean Challenge, limited robustness during collaborative planning, and the need for more low-latency navigation policies directly from sensor data in dynamic and degraded scenes. The latter can possibly be addressed with the emergence of learning-based methods as demonstrated in attractive domains such as drone racing. Aerial field robotics is a growing field, and the innovative work from individual research teams, cross-fertilization between industry and academia, and ambitious robotics competitions will continue to set milestones in the domain. The research efforts for resilient autonomy will be defining towards rendering aerial robots widely and reliably utilized in a host of diverse and challenging applications in complex industrial and natural environments. In this context, focused research on perception, planning, control and learning, as well as efforts for a unified perception-action loop are particularly important.

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