Cooperative UAV Autonomy of Dronument: New Era in Cultural Heritage Preservation

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***Abstract*—Digital documentation of large interiors of historical buildings is an exhausting task since most of the areas of interest are beyond typical human reach. We advocate the use of autonomous teams of multi-rotor Unmanned Aerial Vehicles (UAVs) capable of agile control while perceiving the environment and planning in real time using on-board computation only. Autonomous UAVs speed up the documentation process by several orders of magnitude while allowing for a repeatable, accurate, and condition-independent solution capable of precise collision-free operation at great heights. The developed multi-robot approach allows for performing tasks requiring dynamic scene illumination in large-scale real-world scenarios, a process previously applicable only in small-scale laboratory-like conditions. Experimental analyses range from single-UAV imaging to specialized lighting techniques requiring accurate coordination of multiple UAVs. The system's robustness is demonstrated in more than two hundred autonomous flights in fifteen historical monuments requiring superior safety while lacking access to external localization.**

I. Supplementary Material

The paper is supported by video available at youtu.be/Gx-mBklSbYc.

II. Dronument — Autonomous Aerial Robotics for Heritage Digitalization

Documenting interiors of historical buildings for the purposes of restoration planning and documentation works is an expensive task. Although the task is extremely challenging from a robotics view, aerial autonomy can lower the costs significantly. Such an aerial autonomy needs to be capable of real-time perceiving, planning, and acting, which need to be safe, reliable, lightweight, and independent on the characteristics of the environment. Precisely these requirements are challenged within a multidisciplinary project Dronument (*drone & monument*) [1], [2] which introduced a universal autonomy for UAVs cooperating within a team while documenting the interiors of historical monuments for assessing their cultural and structural state. The Dronument proposed a fully on-board single-robot autonomy and active multi-robot cooperation enabling documentation tasks requiring dynamic scene illumination in large-scale real-world scenarios, a process previously applicable only manually in areas easily accessible by humans. Note that this paper presents a concise summary of [1].

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Fig. 1: Two aerial robots cooperating during a documentation task. Each UAV perceives, plans, and acts in real time on the basis of its own on-board perception and a mission plan. The multi-robot cooperation scheme respects the desired illumination defined by the documentation task.

The Dronument interconnects cultural and technical institutions to develop a robotic solution, which has been deployed fully autonomously in a plethora of characteristically diverse historical monuments. The experimental analyses presented in this paper and in [1] utilize UAVs in multiple real-world documentation tasks, and discuss the quality of the obtained results used in subsequent restoration works, as well as suitability of particular techniques for UAVs. The analyses demonstrate the framework's robustness in single and multi-robot deployments in more than two hundred fully-autonomous flights in fifteen historical monuments. In these experiments, the aerial robots rely solely on onboard sensors without access to external localization (such as global navigation satellite systems (GNSSs) or motion capture systems), perceive the environment under varying lighting condition, and plan their trajectories with the perception system in the feedback. The perception, path & mission planning, and control modules are coupled to achieve resilient real-time performance.

The unique and extensive experimental campaign of Dronument brought numerous lessons learned that are transferable to other safety-critical robotic missions in documentation and inspection tasks. The system also serves as a large part of an official methodological study approved by the Czech National Heritage Institute for its high added value in heritage protection. The methodology (available at [2]) describes the proper usage of UAVs in historical structures for the first time and so prescribes the proposed system to be a standard in this application.

III. Robotics and Automation in Cultural Heritage Preservation

Documentation and digitalization of historical objects requires gathering various types of data, e.g., camera images in visible, infrared (IR) and ultraviolet (UV) spectra, and 3D models. The data gathering is demanding in both time and human resources, particularly in large buildings. This motivates the endeavor to automate data gathering by introducing mobile robotic solutions capable of fast autonomous documentation. The first level of mobile-robot automation can be achieved by applying Unmanned Ground Vehicles (UGVs) as carriers of the documentation sensors. A UGV equipped with a laser scanner and capable of autonomous navigation in constrained environments can sequentially visit several locations to collect a set of scans covering the entire operational space [3]. An advantage of this approach lies primarily in reducing necessary human participation in the scanning process, allowing for the collection of scans from potentially dangerous areas. Several systems applying such an approach were already developed and deployed for scanning historical monuments [4], [5].

Whereas the operational space of UGVs usually does not exceed typical human reach, multi-rotor UAVs capable of 3D navigation in confined environments can be applied for data collection tasks in difficult-to-access areas. In exteriors, UAV solutions abundantly utilize predefined GNSS poses for navigation [6]. In contrast to exteriors, the applicability of UAVs in interiors imposes additional challenges — lack of GNSS localization, navigation in a confined environment, and non-negligible aerodynamic effects. Because of that, UAV systems deployed for indoor data gathering are mainly limited to industrial inspections, with only a few works targeting UAV-based documentation of historical buildings. The specifics of such an application are targeted in this work.

For industrial inspections, the literature typically exploits the environment structure, such as known profiles of tunnels [7] or structured and well-lit warehouses [8]. Nevertheless, aerial data gathering inside historical buildings is rare. A specialized platform for assisting in cultural heritage monitoring called *HeritageBot* was introduced in [9]. However, no evidence of the deployment of this platform in historical monuments is presented. In [10], the authors propose an assistive system to manual control of the UAV during inspection tasks with the experimental deployment of the system inside and outside historical sites.

Among introduced solutions, the most advanced UAV-based systems with the high level of autonomy required for the interiors of historical buildings were introduced in our recent works [1], [11]–[14]. In these publications, we introduced a preliminary application-tailored autonomous UAV system allowing for safe localization and navigation inside historical structures [1], the methodology and algorithms for the realization of advanced documentation techniques found in reflectance transformation imaging (RTI) [12] and raking light (RAK) [13], and an autonomous single-UAV system for realization of documentation missions [14]. All works provide a fully autonomous solution and the possibility of performing documentation techniques in difficult-to-access areas without using mobile lift platforms or scaffolding installation. The main contribution of our approach is novel realization of documentation techniques that could not have been realized with only a single robot in principle.

Nevertheless, the entire state of the art [3]–[10] focusing on cultural inspection and documentation utilizes classical robotic approaches. The primary reason for this are the safety guarantees provided by the classical approaches, which are widely-studied in comparison to alternative methods, such as end-to-end perception-to-control learning. That is also true for our methodology [1], [11]–[14], which maximizes its safety and resiliency whilst working in real-time by having the integration of perceptual, planning, and control modules loose. This is to provide a safety-aware way to analyze correctness of different modules, independently on others.

IV. UAV-based Framework for Documentation of Cultural Heritage Interiors

The overall pipeline of the UAV-based framework for interior documentation in historical monuments is showcased in Fig. 2. The framework is composed of three main phases — the *pre-deployment phase* incorporating pre-flight data gathering and mission planning, the actual *deployment of the system* in interiors of historical buildings, and *post-deployment phase*, including processing and utilization of the collected data. During the deployment of the system, the UAVs use the reference scanning plan and the 3D representation of the environment as an input for the autonomous documentation mission. Each UAV is running a high-level mission control module and an autonomous navigation stack onboard. The high-level mission control module handles the communication with other UAVs and a human supervisor and adapts the behavior of the UAV based on received requests and information.

The autonomous navigation stack integrates perception, planning, and control modules to allow safe navigation in the environment. In particular, a bank of Kalman filters [15] extended with smoothing over a short past-measurements buffer [16] fuses onboard inertial measurements with localization output produced by slow-drift pose estimation method LOAM [17]. An a-priori shared map of the environment enables multi-robot coordination and repetition of missions by deriving a global frame and also provides an additional safety level by allowing robust online analysis of localization drift and cross-checking of sensory measurements. The trajectory planning designed for multi-UAV teams in the scope of the application is described in detail in [18]. This planning applies the pre-planned reference path and the current perceived state of the environment (including detected obstacles that are not present in original representation of the environment) as an input to MPC-based method for generation of dynamically feasible collision-free trajectories [19] that serve as reference for a low-level SE(3) controller [15].

V. Experiments and Results

The extreme requirements on safety imposed by the nature of the application requiring the deployment of UAVs in priceless historical buildings imply thorough validation of all the developed software and hardware solutions prior to their deployment in real-world missions. The software solutions ranging

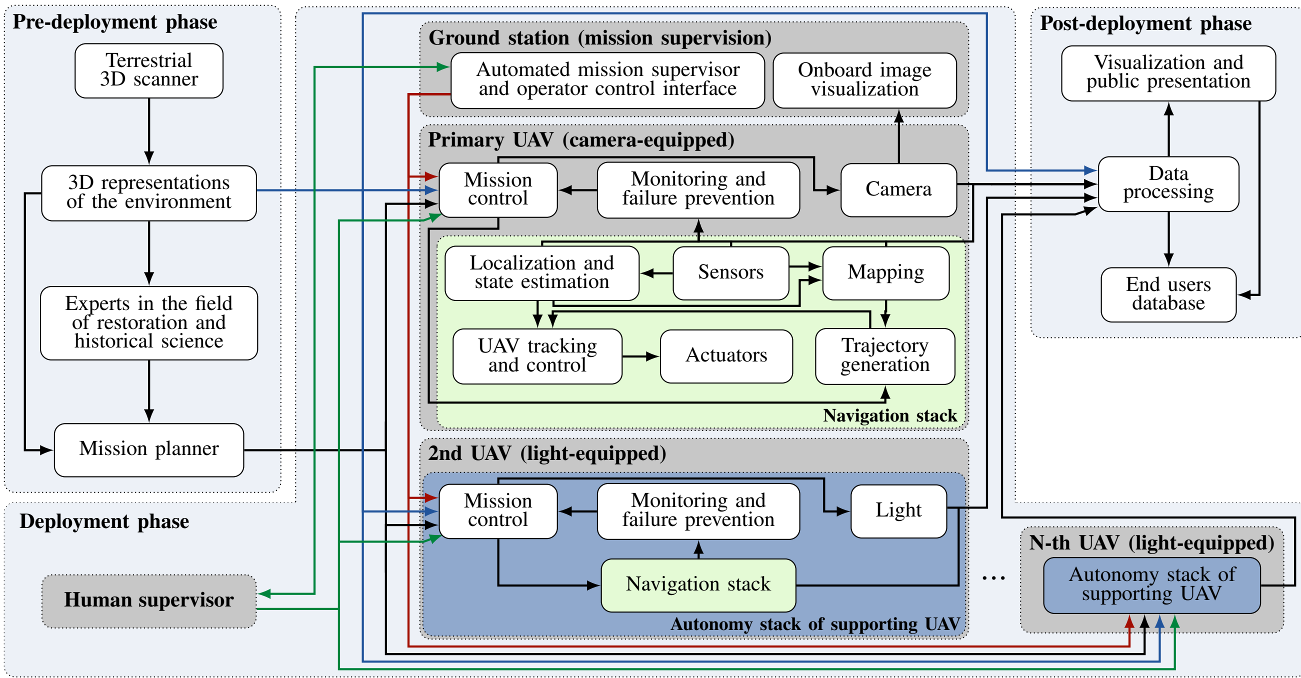

Fig. 2: High-level diagram of the three-phase architecture of the system designed for multi-UAV documentation of interiors of historical buildings. The 3D model of the environment and the mission plan are used as an a-priori generated input for the realization of the documentation mission itself. After the deployment phase, the data gathered during the mission are processed and provided to the end users.

from the state estimation and control algorithms to high-level mission control were intensively tested with the use of Gazebo simulator and the MRS simulation package[1] providing realistic behavior of the UAVs.

The final version of the system, as presented in this manuscript and in [1], builds on preliminary versions and architectures of both software and hardware stacks and integrates experience from over a two year period of experimental deployments. During the experimental campaigns, remaining sources of potential failures were identified and the UAV system upgraded to reach the desired performance and reliability while increasing the number of realizable documentation techniques. The entire system was, to this day, deployed in real-world missions in fifteen historical buildings of various characteristics, including two UNESCO World Heritage Sites, Archbishop's Chateau in Kroměříž and Chateau Telč, with almost twelve airborne hours. The realized documentation techniques cover the traditional visible spectrum photography, imaging in UV and IR spectra and also specialized documentation techniques requiring multi-robot approach such as raking light and RTI.

Imaging in the visible spectrum is the most frequently applied technique as it includes methods providing the widest range of practical information while being relatively easy to perform. Within the fifteen historical structures, objects of interest (OoIs) of various characteristics have been imaged by autonomous UAVs. These OoIs range from artistic elements, such as paintings, stained-glass windows, mosaics, stuccoes, and murals located in the uppermost parts of the main naves, to complex 3D structures, such as window frames and altars up to 20 m high. Additionally, objects may include structural damage, such as crevices, cracks, or fractures.

RTI documentation technique requires a set of images captured by a static camera under illumination from diverse but known poses. These inputs are then used to generate a polynomial texture map representation that allows a virtual interactive relighting of the captured object from an arbitrary direction. To validate whether the proposed system is feasible for RTI, it was applied to document a vault located 11 m above ground in St. Anne and St. Jacob the Great Church in Stará Voda. The RTI was realized in two comparable configurations: 1) with the camera (with telephoto lens) mounted on a static tripod with a clear, but unaligned view on the vault and 2) with the camera mounted on board the primary UAV. In both configurations, the light was carried on board the secondary UAV, with the directions of illumination being derived from the poses of this UAV, as estimated on board during the flight.

Although the fully UAV-based approach yields lower image quality since the camera's pose is not static over time, it has wider operational space and enables imaging from appropriate angles, as was verified for other OoIs in the church that could not be reasonably captured by a static camera at all. The non-staticity of the camera's reference pose misaligns the images; thus, their sub-pixel post-alignment is required to avoid blur in the resulting polynomial texture map (PTM). The experiment shows that the fully UAV-based approach yields comparable results to the single-UAV approach, which is favorable when the OoI can be photographed from the ground — an impossible scenario for most OoIs in difficult-to-reach areas of historical buildings.

Realization of documentation techniques applying illumination and sensing in IR and UV spectra (reflectography and

[1] github.com/ctu-mrs/simulation

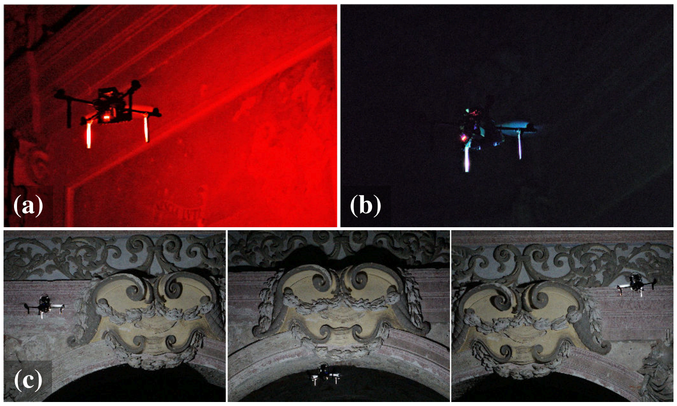

Fig. 3: Deployment of UAVs carrying IR (a), UV (b), and visible-spectrum (c) source of light. The dynamic lighting during RTI (c) requires the perception system to be robust towards varying scene illumination.

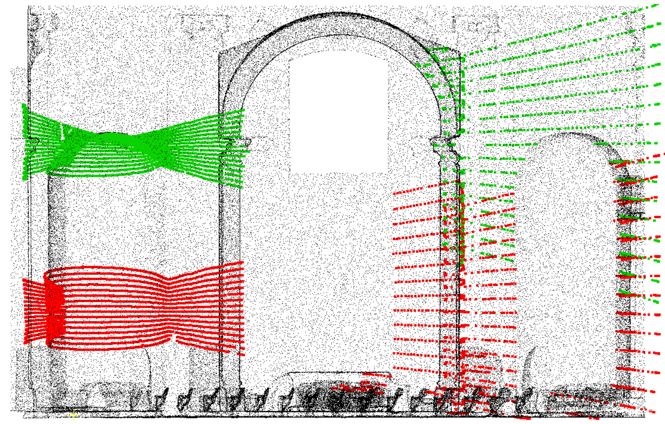

Fig. 4: Common vertical symmetricity of tall historical monuments causing geometrical degeneracy in LiDAR-based localization. Localization in such environments is achievable with state-of-the-art methods for well-constrained problems (in green). However, when a robot's perception is under geometrical degeneracy, the geometrical ambiguity (vertical ambiguity in red) makes the estimation challenging.

fluorescent photography) is methodically similar to visible spectrum photography (VIS). However, in contrast to VIS, these methods require higher exposure times (up to tens of seconds), that put stricter requirements on image stabilization in the presence of onboard vibrations, inaccuracies, and disturbances that cause UAVs to deviate from their reference pose. In case of reflectography, the high exposure times make the use of UAVs for imaging in UV and IR unfeasible. However, supporting ground-based imaging with aerial lighting is applicable. The IR and UV-based methods were tested in St. Anne and St. Jacob the Great Church, Stará Voda (see Fig. 3) and in Church of the Holy Trinity, Běhařovice. The experiments showed that the proposed system can be used in realization of the UV and IR-based methods in historical structures, even in limited lighting conditions.

The extensive experimental campaign provides an exhaustive validation of the proposed system in real-world conditions and supports its applicability in GNSS-denied environments by identifying and overcoming challenges imposed by specific scenarios. Apart from higher efficiency and safety of autonomy in contrast to human-controlled flying, a fully autonomous system allows flight in close proximity to obstacles, enlarging the operational space of the UAV. This is advantageous particularly when documenting elevated OoIs where the inaccuracy in estimating the UAV's distance to the ceiling is proportional to the distance from the human eye, thus making manual navigation in these areas unsafe.

VI. Discussion

The proposed UAV-based system for documenting historical monuments of differing structures, dimensions, and complexity has demonstrated its wide applicability in real-world documentation tasks, ranging from RGB photography and 3D mapping to multi-robot RTI in areas high above the ground. The high level of autonomy, the ability to fly beyond the visual line of sight between the UAV and a human operator, and the deployability in low lighting conditions enable to gather crucial data for heritage protection and documentation that was not possible before. This novel system has been used in the very first fully-autonomous multi-robot real-world deployments in such complex and safety-demanding interior structures, which showcases the immense potential of mobile robots for fast, accurate, and mobile digitalization of difficult-to-access interiors.

The study also assists in identifying the current challenges and future directions of research in aerial documentation and inspection. Although the research effort is mostly targeted towards autonomous systems adaptable to general environments, some applications, such as documentation of historical buildings or other safety critical applications, asses the quality of the system according to different criteria. The design of systems for such applications are mostly guided by the requirements on robustness, reliability and well-defined behavior of the system that allows early recognition of the system's failure by human supervisor. These requirements constrain the set of applicable algorithms and favor the established, well-tested methods that are integrated in a way that allows analysis of the performance and defining theoretical guarantees of the system. Although the tight integration of perception, planning and control modules can lead to improvement in robustness and accuracy, the current lack of determinism and theoretical guarantees on the system's performance hinders its use in safety-critical applications. Once theoretical guarantees, determinism, and field testing of novel uncertainty-aware semantics-based systems are achieved, the advantages of these approaches can indisputably lead to improvements of current technology designed for interior documentation. These include uncertainty-aware planning, perception-aware control for obstacle avoidance, and semantics-based documentation.

Of particular interest should be uncertainty-aware pose estimation in geometrically structureless environments. In tall historical monuments, vertical symmetricity generates geometrical degeneracy in LiDAR-based localization (see Fig. 4). This makes the pose estimation inside such buildings challenging. Systems capable of quantifying the degeneracy and plan and act with respect to this estimate shall improve robustness in such safety-critical applications.

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