Documentation of Historical Buildings with the Usage of Model Predictive Control

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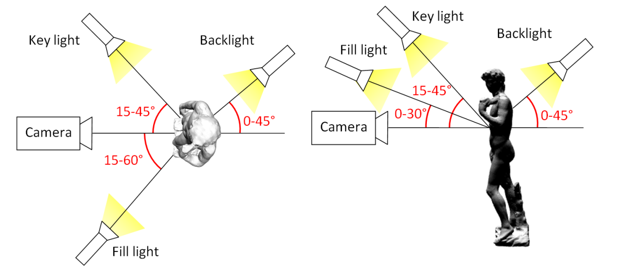
I. Extended abstract

A novel system for autonomous documentation of interiors of historical buildings by a group of cooperating Unmanned Aerial Vehicles (UAVs) is presented in this paper. The main motivation of documentation of historical buildings is a necessity of monitoring of the state of frescoes, statues and paintings, where the early detection of smaller defects can prevent damage to valuable historical art pieces. Since modern sensors for automatic data acquisition like high-resolution cameras or laser scanners can provide sufficient data by a remote or distant measurement for state analysis and defects detection, historians and restorers do not need to get close to art pieces in person to inspect their state. However, these sensors are usually constrained by line of sight and limited range to provide required precision. In complex and large historical objects, where the remote sensing is especially needed, classical approaches have to be supplemented by methods relying on mobile sensory carrier to reach locations unreachable from ground. The proposed techniques may provide data from locations that are currently not reachable without building a costly scaffolding, which also limits everyday usage of the objects. Hence, often places like recesses or frescoes on the ceilings of cupolas were not inspected for hundreds of years.

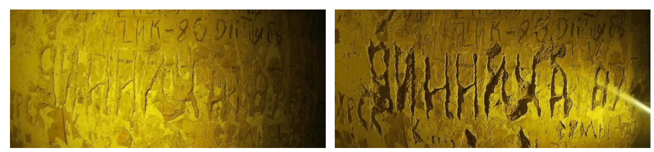
To be able to provide sensory data and multimedia documentation from these locations, we propose to employ multi-rotor unmanned helicopters, due to their high maneuverability close to obstacles, capability of stable hovering without a significant relative motion to their surroundings and the ability to control their heading independently of the direction of their motion. The necessity to utilize a group of UAVs is given by the requirement of setting lights in different angles relative to the camera (typically from 15 up to 90 degrees), which prevents the flatness of the resulting image and provides more valuable information for later processing. Our system is inspired by three points lighting and strong side lighting techniques, which are used by historians and restorers nowadays. The benefit of the first one (shown in Figure 1) is that it enables to better capture the three-dimensional reality in a flat image with the usage of shadows. The second one is based on the setting of light to an object being shot in as small angle as possible. This approach highlights the roughness of the surface, which causes the shadows in the image. The difference between an image of the painting taken with the direct lighting and with the strong side lighting is shown in Figure 2.

Since the UAVs carrying a camera and lights are supposed to fly a few meters from each other in hardly visible regions during the missions, the autonomous control of their motion is essential. For this purpose, we have implemented a leader-follower approach together with a Model Predictive Control (MPC) method based on our previous works on formation control and trajectory tracking [1], [2], [3]. The optimization process within the MPC framework is done in four periodically repetitious consequent steps. Firstly, the trajectory of the leader, which is supposed to be defined by historians together with the objects which have to be scanned, is used as the input for the first optimization step, responding for position control of the leader. The leader motion planning is solved as a multi-objective optimization, where deviations of the UAV from the desired position, obstacle avoidance, mutual collision avoidance, limitations on control inputs and motion constraints are taken into account in the objective function. This step is followed by running the optimization task for smooth correction of camera heading directly to the scanned object.



(a) top view (b) side view

Fig. 1. Common setting of lights in three points lighting method



(a) direct lighting (b) strong side lighting

Fig. 2. Difference between inscription graven in the wall taken with a direct lighting and with a strong side lighting. Photos taken by a drone in Church Stara Voda.

In the third stage, based on the trajectory obtained in the previous step and the predefined formation scheme, desired trajectories of the followers are computed. The followers motion planning is again defined as an optimization task, similar as for the leader, but with slightly different objective function, which also includes a term penalizing presence of the follower in the field of view of camera carried by the leader. In the last step, the optimization task for smooth correction of light heading is solved to ensure the correct lighting of the object. The more detailed description of the above-mentioned objective function is presented in [4].

Prior to the real deployment, the proposed system was successfully tested in simulations in complex scenarios inspired by the interiors of St. Nicholas Church at Old Town Square in Prague (for resulting trajectories in one of the scenarios see Figure 3). The first real experiments were performed in the outdoor environment with the hexacopter with DJI F550 frame (see [5] for more detailed description of the system). In these experiments, a feasibility of the proposed solution was verified. Snapshots from the experiment are shown in Figure 4.

After the initial experimental verification, the system was deployed in several real application in cooperation with restorers and historians in St. Nicholas Church in Prague, in Church Sternberk, Church Stara Voda (https://youtu.be/yNc1WfebIag), Church of St. Maurice in Olomouc (https://youtu.be/cXa2yBLAeY) and Grotto Gorzanow (https://youtu.be/6mRYxciDLCM). The key challenges that have to be solved in these scenarios are global localization of UAVs in the GPS denied environment and also mutual localization of individual team members. In different campaigns, we tested different localization approaches, such as slam with low-weight and low-cost sweep laser scanner [6], indoor GPS [7], and optical flow from down-looking camera. The indoor GPS produced by Marvelmind company has an impressive precision (around $3\,cm$ in more than 90% of measurements), but in the case of lower signal the measurement is unreliable and the system often does not provide any data for a few seconds (see Figure 5 for the comparison of measured data and the reference path). The disadvantage of optical flow-based localization is mainly the drift, but locally it provides a reliable source of information for UAV stabilization. Reliability of the tested SLAM approaches strongly depends on the diversity of the surrounding environment, which is usually present in historical buildings, we have experience with. Nevertheless, it also cannot be a sole source of position information, since the required properties of the neighboring environment cannot be guaranteed in all missions. To get the reliable estimation of the position, we propose to rely on a combination of these different approaches via a sensor fusion mechanism.

In addition to precise information about the position within the building, the relative position to other members of the formation has to be known to ensure proper light setting and reliable mutual collision avoidance. Some systems providing relative localization using onboard visual markers and cameras were already developed within our group [8], [9]. Usually for the purpose of stabilization of UAVs within swarms [10], [11], [12] and heterogeneous teams of Unmanned Ground Vehicles (UGVs) and UAVs [14], [15] in GPS-denied environments. Nevertheless, the specific application of documentation of interiors of churches and similar historical buildings require operation of the system in environment with light conditions insufficient for these vision-based methods. Being motivated by these needs, we have designed a novel relative localization system using nearly ultra-violet markers [16], [17]. Due to the usage of nearly ultra-violet spectrum, which is rarely emitted in nature as well as indoors, the functionality of this system is almost independent of the light conditions and may be used even in dynamically changing light conditions. Thus this system enables fast onboard relative localization without the need of adding any heavy equipment to a UAV frame.

ACKNOWLEDGMENTS

The work has been supported by the project no. DG18P02OVV069 in program NAKI II, by the Czech Science Foundation (GACR) under research project No. 17-16900Y, and by the Grant Agency of the Czech Technical University in Prague under grant No. SGS17/187/13.

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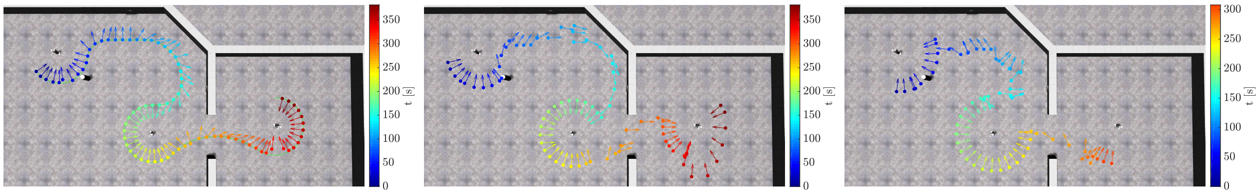


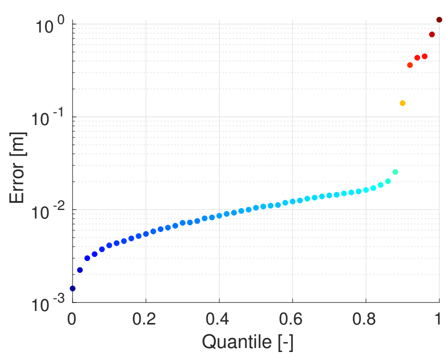
(a) leader (b) follower with the key light (c) follower with the fill light

Fig. 3. Results of the verification of the proposed method in the simulator Gazebo. The dotted line shows the initial trajectory and the arrows denote the trajectories, which were consecutively planned by particular UAVs in the formation during the mission.

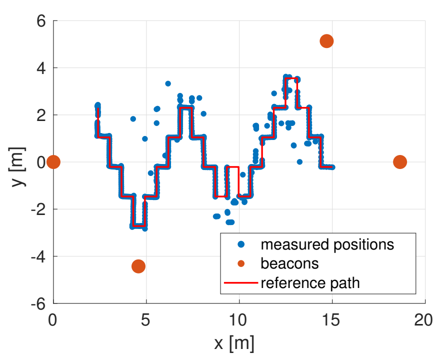
(a) 0 s (b) 8 s

(c) 17 s (d) 24 s

Fig. 4. The experiment in simulated outdoor scenario which tests the ability of formation to smoothly switch between consequent objects of interest. Particular images consist of side view of the formation (left part) and the image from the onboard camera mounted on the leader UAV (right part). The dotted circles highlight particular UAVs - leader (green), follower with the key light (red) and follower with the fill light (blue).



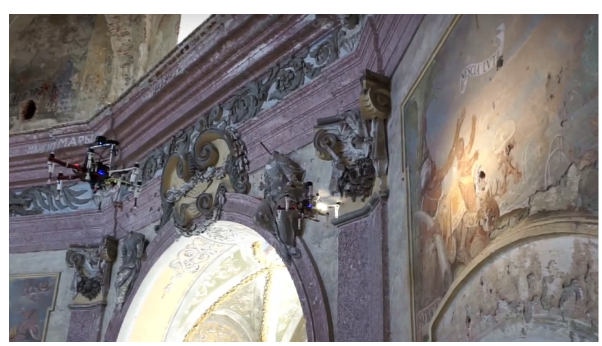
(a) quantiles of precision



(b) comparison with reference path

Fig. 5. The results of the experiment with Marvelmind indoor GPS in indoor environment

(a)



(b)

Fig. 6. Demonstration of the implemented methods of lighting within our system - three points lighting method without the back light (a) and strong side lighting method (b).