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AERIAL ENVIRONMENTAL MAPPING IN RECONNAISSANCE ROBOTICS
BEZPILOTNÍ PRŮZKUM PROSTŘEDÍ V MOBILNÍ ROBOTICE

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ABSTRACT

In the last decade, aerial photogrammetry performed with small unmanned aircraft systems has been developed into a progressive technology applicable across multiple fields and branches. The regular approach employing control points for georeferencing is characterized by high accuracy and reliability; however, it can also be considered generally unusable in some special scenarios. This thesis has been conceived to design and discuss a sensor system that allows direct georeferencing in unmanned photogrammetry; in this context, the author also proposes relevant calibration methods and verifies the performance of the entire setup. A significant portion of the presented research involves identifying new opportunities for the novel mapping method. Two of the potential applications are characterized thoroughly: Environmental mapping, namely, the determination of snow cover parameters, and robotic radiation search. These activities embody tasks where the system enables us to eliminate the human health risks associated with a concrete environment. The actual benefits and overall usability are assessed within real-world experiments.

KEYWORDS

Aerial photogrammetry, unmanned aircraft systems, mobile robotics, environmental mapping, CBRNE.

ABSTRAKT

Letecká fotogrammetrie v oblasti bezpilotních systémů představuje rychle rozvíjející se obor nalézající uplatnění napříč nejen průmyslovými odvětvími. Široce rozšířená metoda nepřímého georeferencování založená na vlícovacích bodech sice dosahuje vysoké přesnosti a spolehlivosti, v některých speciálních aplikacích nicméně není použitelná. Tato disertační práce se zabývá vývojem senzorického systému pro přímé georeferencování aplikovatelného na malých bezpilotních prostředcích a dále také návrhem vhodných kalibračních metod a testováním přesnosti. Významná část práce je věnována novým oblastem, kde může navržený systém pomoci eliminovat bezpečnostní rizika spojená s daným prostředím. V tomto kontextu byl systém testován v reálných podmínkách při mapování sněhu v horských oblastech a při robotickém mapování radiace.

KLÍČOVÁ SLOVA

Letecká fotogrammetrie, bezpilotní letadla, mobilní robotika, environmentální mapování, CBRNE.

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Part I.

Preamble

1. Introduction

At present, unmanned aircraft embody a very progressive and fast-growing technology. Although pilotless flying vehicles have existed since the second half of the 20$^{\text{th}}$ century, they have been almost exclusively utilized by the military for reconnaissance and weapon carrying purposes. At the turn of the millennium, the technological advancement and descending cost of key components produced an increased interest on the part of civil corporations and institutions, such as universities, science centers, and commercial subjects. In this context, multi-rotor machines have become especially popular, representing a concept very different from that of the military vehicles employed in the previous century. This category gained in importance mainly thanks to the aircraft's ability to hover and handle relatively weighty payload with respect to its size.

A massive expansion of unmanned aircraft systems (UAS) occurred in the last decade. In the U.S., the number of registered unmanned vehicles reached 1.5 million at the beginning of 2020 (considering both commercial and leisure operators) [1], and up to 2.8 million items are expected in 2024 [2]: In other words, the market may double within four years. However, the actual numbers can be much higher, as not all of the vehicles are subjected to registration, with a certain amount operated illegally. In the Czech Republic, where commercially used UASs are registered, the count has grown from 27 in 2012 to 3,155 in early 2020 [3]. Major interest is observable also within the scientific community: *Web of Science*, a leading citation database, contains more than 5,000 UAS-relevant records published in 2019, while fewer than 800 items had been released in the year of 2010[1] (Figure 1.1).

Today, it seems almost impossible to believe that the currently most famous commercial UAS manufacturer, Shenzhen DJI Sciences and Technologies Ltd., better known as DJI, released their first consumer-grade UAS *Phantom* not long ago, in 2013. Presently, DJI has a global market share of approximately 70% [4]. Most of the aircraft sold range within the consumer category; however, a visible trend to cover the professional and industrial segments has appeared in the recent years.

The term *UAS* is typically used to denote systems including aircraft without a human pilot aboard, i.e., unmanned aerial vehicles (UAVs) and associated elements such as a ground station, communication system, and support equipment. The diversity of the sys-

[1] The search was limited by the following terms contained in the title, abstract, and keywords of indexed articles and proceedings: UAS, UAV, drone, unmanned aircraft system, unmanned aerial vehicle, unmanned aircraft, RPAS, remotely piloted aircraft system. The data are valid for 2 July 2020, and they do not reflect the research outcomes unpublished or unindexed to that date.

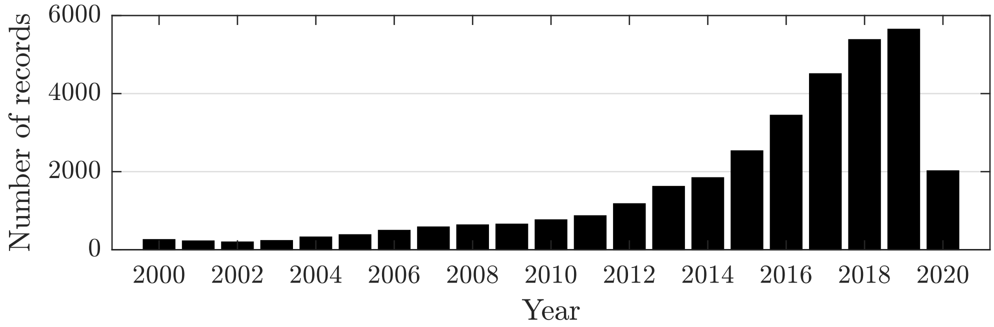


Figure 1.1.: The number of UAS-related articles and proceedings indexed by the *Web of Science* database according to the publishing year (non-cumulative graph).

tems is enormous: The dimensions and weights vary from, for example, 20 meters and 18,000 kg (wingspan and gross weight) in the well-known *General Atomics MQ-9A Reaper* unmanned combat aerial vehicle [5] to 0.3 m and 0.9 kg in the *DJI Mavic 2*, a popular consumer-grade vehicle [6]. This thesis focuses on commonly available commercial UASs and aircraft utilized in the civil sector, assuming size and weight values that enable single-person manipulation and operation. The discussed vehicles are very promising in many segments, predominantly thanks to the following benefits: low cost, wide availability, and easy and safe operation. Unmanned aircraft can be classified according to other parameters too, such criteria comprising endurance, maximum speed, and reachable altitude; the most important factor, however, rests in the maximum take-off mass (MTOM), which plays a substantial role even in the new European Commission regulation 2019/945 [7]. According to this categorization, the above-defined aircraft fall within the C2 and C3 classes, where the corresponding MTOM limits are 4 and 25 kg, respectively; in the literature, the UAS categories are often called light, mini, or small. The discussed aircraft typically allow flying with an extra payload of up to several kilograms, a value sufficient for the objectives of this thesis.

Alongside the rapid expansion of civil unmanned systems, many new options have opened up across diverse fields, yielding applications previously deemed unfeasible via piloted vehicles, due to, above all, economic reasons, safety concerns, or a lack of suitable technologies. Consequently, the current usage includes, among others, automatic package delivery, security and monitoring, close-range inspection and remote sensing, pesticide spraying, entertainment purposes (such as movie shooting), search and rescue operations, and leisure tasks. From the professional perspective, remote sensing in particular has gained immense popularity across multiple industries. Generally, this technique involves acquiring information about objects or the Earth in a contactless manner and may be performed via passive (e.g., visible and infrared imaging) or active sensors, including, for example, a radar or a LiDAR. The former of these two approaches is by far the more widely utilized one, especially as regards image sensor-based passive sensing in the visible spectrum: The sensors are usually cheap and light-weight, thus being appropriate for every UAS class. Moreover, thanks to the present computer vision (CV) algorithms and computing power, the image data are suitable for not only producing the actual aerial imagery and orthophotos but also generating high-resolution spatial data, such as point clouds and digital elevation models (DEM). This technology is basically known as photogrammetry.

Unmanned aircraft, along with photogrammetry, became a true game changer in many industries. The technique proved to be useful in estimating snow depth in the Arctic [8], performing tree inventories [9], inspecting transmission lines [10], monitoring crop height [11], visualizing archaeological sites [12], detecting topographic changes [13], computing stockpile volumes [14], monitoring radiation waste storage facilities [15], inspecting bridges [16], and many other activities. The papers, in general, emphasize similar benefits compared to conventional methods, namely, the low operation cost, easy and fast deployment, and superior resolution.

As the photogrammetric results are commonly processed via geographic information systems (GIS) to supplement other map layers or loaded in other software tools to extract dimensions and object sizes, compute volumes, or analyze trends, accurate georeferencing constitutes a vital procedure. A widespread technique rests in indirect georeferencing, a method utilizing ground control points (GCP) visible across the aerial imagery to deliver reliable, highly accurate outcomes even with inexpensive onboard sensors. Conversely, direct georeferencing, which relies on precise onboard sensors, is somewhat less popular: The approach is characterized by considerable complexity of the system, the necessity to perform inter-sensor calibration and synchronization, lower accuracy and reliability, and an overall higher cost. However, against these drawbacks there also stand several indisputable benefits, including but not limited to independence from the ground targets, an aspect that endows the method with wide applicability in many industries, those that involve environments featuring major accessibility difficulties or safety risks in particular.

The topics relating to GCP-independent remote sensing have constituted the main research interest of the author of the thesis since 2014. At that time, this subdomain was rather marginal within small unmanned aircraft; however, the expansion of UASs and associated applications in the present decade has contributed to the broader focus on the discussed topic. The outcomes of the thesis are then to be viewed in this context, as at least some of the author's original results from several years ago may have become relatively common knowledge. Nevertheless, the progress currently observable across the research teams and the commercial sector confirms that the study direction was chosen appropriately; despite this, however, various aspects have not been addressed sufficiently, especially as regards possible new applications.

Last but not least, further dissemination of UAS applications is limited by the legislation, which is only gradually modified to cover the rapid technological advancement, often restricts faster progress, and may embody a bureaucratic burden; such concerns nevertheless appear to be rather irrelevant in affiliated fields, including terrestrial robotics.

The challenges and possibilities of the discussed UAS class are also addressed within the forecast of the Federal Aviation Administration (FAA[2]) [17]:

> *While introduction of UAS in the NAS* (national airspace system, author's note) *has opened up numerous possibilities, it has brought operational challenges including safe integration into the NAS. Despite these challenges, the UAS sector holds enormous promise; potential uses include modelers experimenting with small UAS (sUAS) performing numerous functions such as aerial photography; recreational flying for personal uses; sUAS experimenting with package delivery on a commercial basis; delivery of medical supplies; and provision of support for search and rescue missions following natural calamities.*

1.1. Motivation

The widely employed UAS photogrammetry relies on control points, thus being essentially inapplicable in situations where the ground targets cannot be utilized for some reason; in this context, one can mention potentially hazardous environments, such as those involving chemical, biological, radiological, nuclear, and explosive (CBRNE) risks. For example, the 2011 Fukushima Daiichi nuclear accident showed the potential of unmanned vehicles in inspecting highly contaminated areas (Figure 1.2a); from the author's perspective, the capabilities of the technology were further illustrated by the 2014 Vrbetice (the Czech Republic) incident, where an exploding ammunition depot caused significant damage to immovable property and greatly reduced the land usability options (Figure 1.2b). In similar scenarios, up-to-date, accurately georeferenced orthophotos and DEMs may support the ground operations, including the navigation of terrestrial robots or analyses centered on structural and topographical changes. Human safety risks, however, are omnipresent in natural environments, too. The mapping of snow covers in mountainous regions, a task performable with UASs [18], comprises a serious danger of avalanches, making the deployment of GCPs very difficult 1.2c.

The use of indirect georeferencing is limited also by problems other than human health-related risks: The technique requires good visibility of the GCPs from the air, and sufficient GNSS satellite observation must be ensured to localize the targets; such conditions are hardly achievable in, for instance, dense forests 1.2d. Forest mapping and tree inventorization are commonly carried out via unmanned aircraft, and if the ground work involving GCP deployment were eliminated, the method would offer not only markedly improved applicability but also reduced time of the supporting field activities; such a time-saving scenario may then lead towards effective cost cutting.

The areas where GCP-free UAS photogrammetry embodies a potentially beneficial approach can be summarized as follows:

[2]Federal Aviation Administration embodies the civil aviation authority under the United States' Department of Transportation.

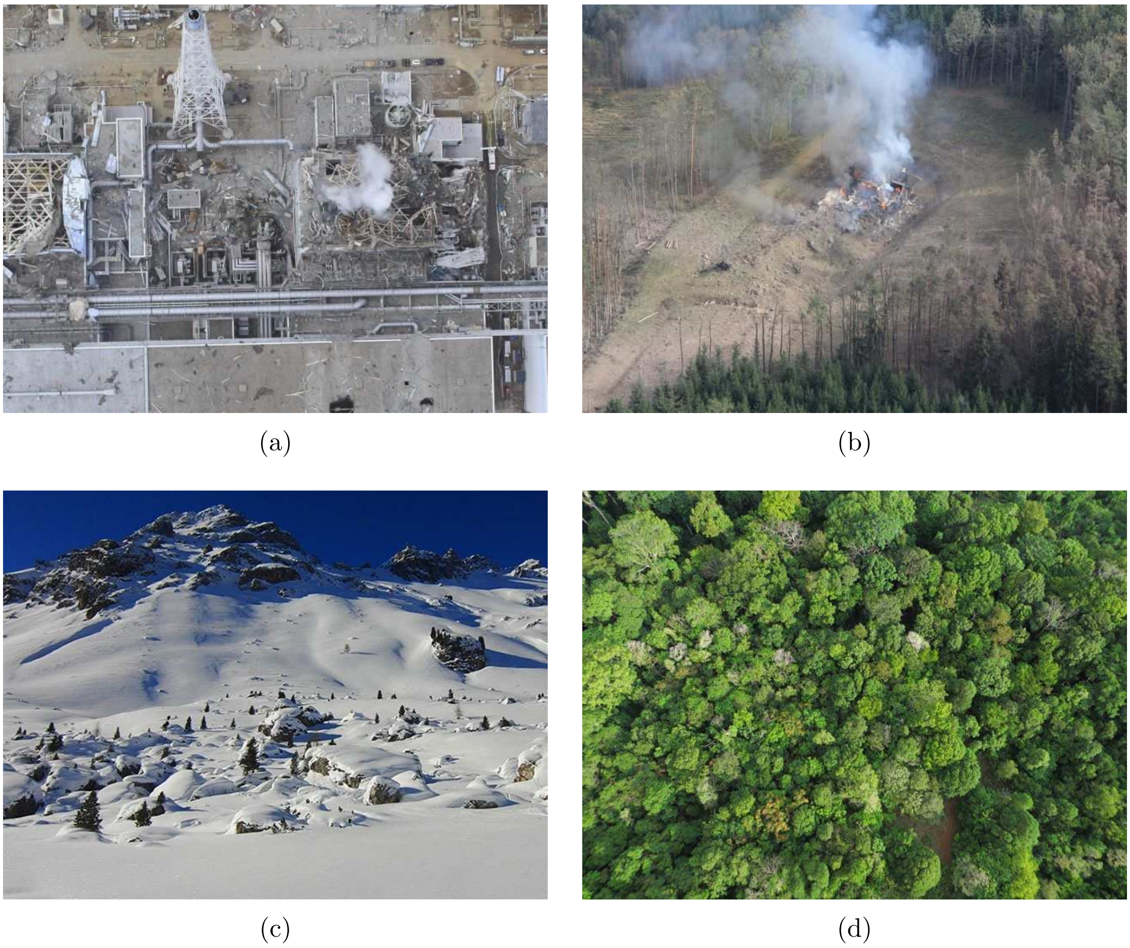


Figure 1.2.: Examples of real-world scenarios where the indirect georeferencing technique is generally inapplicable: the collapsed reactor buildings of the Fukushima Daiichi nuclear power plant after the disaster [19] (a); the ruined ammunition depot in Vrbetice [20] (b); estimation of the snow cover parameters in Alpine terrain [18] (c); dense forest mapping [21] (d).

- Inaccessible areas (e.g., post-disaster locations, mountainous regions).
- Dangerous environments (e.g., environments with CBRNE threats).
- Poor sky visibility areas (such as forests).
- Time-limited operations: The deployment of GCPs is time-intensive.
- Automated missions: Direct georeferencing improves the automation rate of the data acquisition and processing.

1.2. Aims and Objectives

The aim of the research presented herein is to develop a sensor system for ground control point-free aerial photogrammetry performed via small unmanned aircraft. Such a system would expand the usability limits of UASs, especially in human-hostile environments as discussed above. Currently, direct georeferencing is employed rather marginally within the relevant UAS class, as the key component to achieve high object accuracies, namely, the GNSS receiver capable of carrier-phase tracking, was not available until recently. State-of-the-art technologies in navigation systems and digital cameras allow us to construct lightweight photogrammetric tools; despite this advantage, however, various issues and aspects have to be addressed, involving in particular those that relate to system calibration, performance determination, and overall applicability in real-world applications and scenarios.

The central aims of the thesis can be defined as follows:

Aim 1: Developing a multi-sensor system to facilitate direct georeferencing in aerial photogrammetry performed via small UASs; the adopted approach integrates state-of-the-art technologies in the given segment.

Aim 2: Designing a calibration procedure for the system and determining its performance.

Aim 3: Verifying the system's usability and usefulness in real-world conditions and scenarios related to mobile robotics and environmental mapping, above all, missions where the common GCP-based UAS photogrammetry is inapplicable.

1.3. Outline

This thesis discusses the author's main research results via compiling some of his major publications. The actual text is organized into two sections: *Preamble* and *Publications*. The first, or introductory, part proposes the aims and objectives, and presents the *state of the art* in the above-characterized research domains, photogrammetry and georeferencing in particular. Additionally, the *Research Summary* chapter provides an overview of the author's most significant research activities and publications, and the section *Concluding Discussion* summarizes the outcomes with respect to the original goals.

The second portion, *Publications*, is dedicated to selected results produced by the author, containing five full-text papers that cover the entire span of the research activities; four of the articles, namely, one proceedings item and three journal papers, were already peer-reviewed, while the remaining manuscript is currently under review (August 2020). Each publication is introduced by fundamental information on its actual character, version, funding, and the author's contribution.

A complete list of the author's articles, including both those which strongly relate to the discussed field and those concerning different UAS topics, is presented in appendix within the *List of Author's Publications* section.

2. State of the Art

This section summarizes the state-of-the-art in the necessary components to perform the control point-free UAS photogrammetry; namely, the attention is directed to a photogrammetry pipeline integrated within the actual software tools, and georeferencing possibilities and results given by available sensors for the discussed UAS classes. Current trends in UAS photogrammetry deployment within environmental mapping and CBRNE robotics is discussed later in the Publications section with respect to the individual topics discussed therein.

2.1. Photogrammetry

Aerial photogrammetry, a technique that allows obtaining spatial information about objects visible at aerial images, and reconstructing positions, sizes and shapes, is older than digital cameras, GNSSs, computers, and unmanned aircraft, namely, components closely related with the photogrammetry of these days. A fundamental textbook *Photogrammetry* by Prof. Karl Kraus[1] from 1982 [22], and the subsequent editions of this book covered the photogrammetry area thoroughly for the first time. Nevertheless, although the technology changed profoundly, the basic principles describing a camera's central projection in three-dimensional space, collinearity equations, stereoprocessing approaches, aerial triangulation etc. remain unchanged. Thanks to the wide availability of computing power and CV algorithms, the well known principles are presently completed with new methods enabling, for example, high-density geometry reconstruction and fully automatic processing.

Typical photogrammetric products utilized in remote sensing are the orthophoto and items representing the spatial model of the real world, namely, the point cloud, mesh, or DEM. Generating such outcomes from aerial imagery is not feasible by a simple method; the processing is comprehensive and involves numerous different techniques to attain subresults necessary for the subsequent phases (Figure 2.1). Such complete pipelines are currently integrated within multiple professional software tools, such as Pix4D Pix4Dmapper [23], or Agisoft Metashape[2] (formerly known as Agisoft Photoscan) [24], a widely used photogrammetry pipeline tool within a research community.

[1]Institute of Photogrammetry and Remote Sensing, Vienna University of Technology

[2]Agisoft Metashape was exclusively utilized for the photogrammetric processing in all of the author's publications presented in this thesis.

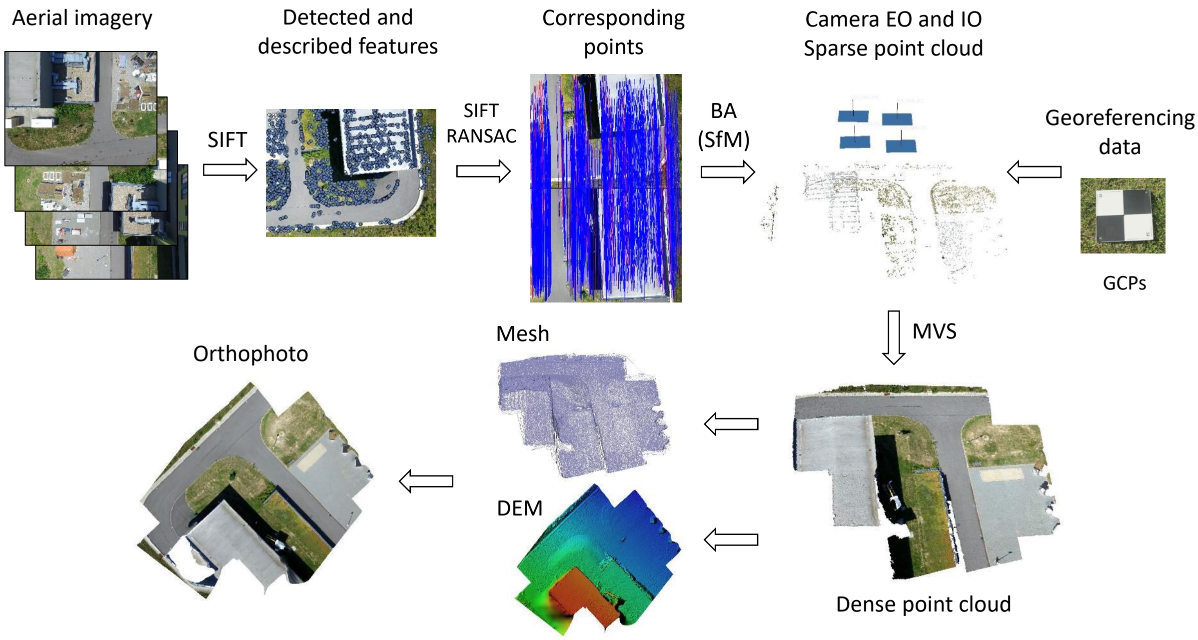


Figure 2.1.: One of the possible processing workflow integrated in current photogrammetric softwares.

An essential task for the geometry reconstruction is to determine corresponding points across the overlapped images; in other words, this activity can be characterized as searching for significant (feature) points in images that have different pixel coordinates but belong to the same object point in the real world [25]. Numerous algorithms for local feature detection and description have been designed thus far; one of the widely employed ones is Scale Invariant Feature Transform (SIFT) [26] and its derivatives. The SIFT algorithm integrates both feature detection, i.e., searching for locations which are locally significant and may be found in other images (corners, typically), and feature description, a procedure involving gradient-based numerical description of the keypoint surrounding. The technique's robustness may be increased by applying an outlayer detection algorithm to filter wrong cross-image matches, for example, RANdom SAmple Consensus (RANSAC) [25]. An evident prerequisite for the feature matching rests in the necessity of a rich and non-repetitive texture, which, together with sufficient lighting conditions, forms a major constraint for the photogrammetry in general.

The detection of the corresponding points typically embodies the first pipeline step, and is a precondition for camera pose estimation and sparse point cloud generation. In the past, this task was facilitated via manually selected tie points visible within overlapped images; however, the aforementioned CV-based technique enables automatic selection of even thousands points securing high robustness of the subsequent processing phases. Although various approaches are available to determine camera orientations (both the exterior and the interior ones[3]), and object point coordinates, the most widely employed

[3]Exterior (EO) and interior orientations (IO) stand for camera extrinsic and intrinsic parameters, respec-

one with respect to optimality and applicability to multiple images is bundle adjustment (BA) [25, 27, 28]. This method encompasses one comprehensive least-square approach to estimate the camera poses and 3D point locations simultaneously, and thanks to the high redundancy facilitated by the significant amount of image corresponding points, the method is further usable in estimating extra unknown parameters – camera intrinsic orientation, for example (BA with self calibration/additional parameters) [22]. The self-calibration ability is one of the central reasons why non-metric consumer-grade cameras find broad application in current photogrammetry.

The point cloud generated by using this method may give us an insight into the scene structure (BA embodies a Structure from Motion (SfM) method); still, such a point cloud is usually very sparse with respect to the considered applications. A dense structure reconstruction is achievable by employing a stereo matching method applied to image pairs or multiple images at once, i.e., Multi-View Stereo (MVS). The algorithms accomplish the given task from the overlapped images and known camera exterior and interior orientations obtainable from, for example, BA [29, 25]. Even though numerous MVS implementations exist, dense pixelwise correspondence search remains the central challenge in this field, especially considering uncontrolled environment with scene and lighting variabilities [30, 29, 31, 32]. State-of-the-art MVS algorithms nevertheless enable us to attain high-density, homogeneous structure reconstruction; however, the results may still not be satisfactory at poorly textured and illuminated areas.

While point-based scene description can be utilized directly in some applications, it is typically converted into a continuous representation, such as a triangle mesh or DEM. The former of these products is commonly used in computer graphics or, in the context of aerial photogrammetry, to generate a textured 3D model of a certain area. The task is achievable via numerous methods; one of the most widely favored ones rests in 3D Delaunay triangulation and its derivatives [33, 34]. The latter option, the DEM, describes the surface model by employing a regular grid of height values. The evident drawback of this format lies in the fact that only one height value is assignable to each cell; still, this representation is well suited for many tasks. The raster models are commonly utilized for spatial analysis in GISs, which enables us to derive slopes, aspect, or detect topographic changes exploiting simple calculations over overlapped, georeferenced layers; another target field is mobile robotics, where the technique resolves navigation problems by means of various path search algorithms. The DEM generation task mainly deals with transforming irregular spatial data into a regular grid, namely, a procedure involving the derivation of height values which have not been observed; a task achievable by an interpolation [28, 35].

The products of the aforementioned processing steps enable us to generate the orthophoto, a typical outcome of photogrammetry that embodies an image of the object in orthogonal parallel projection. Since this type of projection is hardly achievable by

tively; namely, the camera position and attitude, and numerous linear and non-linear IO parameters, such as the focal length, principal point coordinates, and distortion parameters.

employing real cameras, orthophotos are usually composed synthetically, via a known surface model. The process, or indirect transformation, involves four steps: initializing an empty orthophoto image matrix; finding the height coordinate from the surface model at the same horizontal location (this procedure necessarily embodies an interpolation); determining corresponding image coordinates by utilizing the known EO and IO; assigning the image pixel value to the corresponding orthophoto location (this step requires the interpolation of the pixel values) [22]. In aerial photogrammetry, the orthophoto regularly consists of multiple aerial images captured at different time moments and coordinates to cover a larger area; thus, the orthophoto pixel values are determined from multiple images. The achieved parallel projection ensures that the performed distance measurements at the orthophoto equal the distances in the actual reference frame.

Even though the photogrammetric techniques are still being investigated by various researchers and offer many opportunities for improvement, the aims of this thesis do not consist in modifying the processing pipeline, enhancing current methods, or developing new ones; rather than that, the goal is to employ state-of-the-art software tools to support GCP-free remote sensing in complex or novel robotic and environmental mapping tasks.

2.2. Georeferencing

If no georeferencing data are involved in the above-described pipeline, the photogrammetry products may be computed relatively to, for example, the first camera exterior orientation; the usability of such outcomes is, however, somewhat limited. Two major georeferencing approaches are applied in general: indirect and direct georeferencing (IG and DG, respectively). While the former option uses ground control points with known object coordinates, the latter one relies on direct measurements of a camera's exterior orientation parameters. In both cases, the referencing to an object frame can be achieved via multiple manners or within different stages of the processing pipeline. Once a relative photogrammetric model and camera poses have been determined, the referencing may be accomplished by means of 7-parameter similarity transformation involving three translations, three rotations, and one scaling parameter [36, 22, 37]. Even though the least-square method is utilized to find the best fit of the model and the referencing data (GCPs or/and absolute camera EOs), non-linear model deformations cannot be compensated this way. A more suitable approach introduces the referencing data into the BA procedure along with detected corresponding points which leads to the optimal solution with respect to not only matching points and camera parameters, but also the reference points with known object coordinates (GCPs) [28, 36, 22].

Whereas in the case of IG the estimation of a camera's extrinsic parameters forms a vital step, this procedure is not required within the DG, since the positions and orientations of the cameras are estimated directly, exploiting an onboard sensor. Still, the direct use of the estimated EO is not usual (especially in UAS photogrammetry); instead, the values are refined during an optimization process to find the overall best fit. This technique, computer vision-assisted DG, may possibly reduce some errors and increase the accuracy of photogrammetric products in general. Last but not least, the georeferencing approaches could be advantageously combined: Utilizing direct EO measurements together with GCPs may lead to accurate and reliable results even with a small number of control points; moreover, these points could help us to suppress some systematic errors or inaccuracies in the camera calibration.

Obtaining the geographical coordinates of the real-world object points forms an essential task, regardless of the georeferencing approach applied. In the case of the indirect technique, the task comprises determining the coordinates of the GCPs (black and white patterned targets or natural significant points). This step is feasible in multiple ways; most frequently, land surveying equipment, such as total stations and GNSSs, is utilized. The former instrument was designed for accurate angle and distance measurements enabling relative coordinate determination via triangulation techniques and determining absolute locations by comprising points from the geodetic point field. Even though modern robotic total stations allow automatic tracking of moving objects, their main advantage rest in the high reliability and precision during the localization of static object points.

The latter technology is applicable within both georeferencing methods in UAS photogrammetry. GNSS finds wide use across many branches; aerial photogrammetry, however, places higher demands on the accuracy than the prevailing applications. The centimeter accuracy level, namely, the desired precision range in this field [22], is attainable thanks to the carrier-phase tracking technique. Within this approach, the phase of the carrier wave is measured in addition to the standard code-based measurements, enabling us to determine a location with sub-wavelength precision (the wavelengths are approximately 2 decimeter long, depending on the used frequencies). The central problem within this task rests in determining the number of carrier cycles between the satellite and the receiver (rover), i.e., an integer ambiguity search [38]. For this reason, another static GNSS receiver is required to provide observations at exactly known coordinates, facilitating the solution of the ambiguity problem at the rover site. Such a task may be accomplished in the real time or within post-processing, referred to as real-time kinematics (RTK) and post-processed kinematic (PPK), respectively.

The carrier-phase GNSS embodies a suitable technology for the direct camera position estimation; nevertheless, with respect to the UAS dynamics, limited GNSS positioning rate, and the necessity to determine the camera orientation, the sensor system for DG has to be completed with an inertial navigation system (INS). Such devices typically integrate both an inertial measurement unit (IMU) involving accelerometers and gyroscopes for 3D linear acceleration and angular rate measurement, respectively, and a navigation processor to estimate velocities, position, attitude, and other quantities (a task commonly accomplished by using the extended Kalman filter (EKF) [39]) [38]. Due to the cumulative errors present therein, the auxiliary data from an absolute sensor, such as the GNSS or a magnetometer, have to be included in the estimation process. The GNSS/INS integration enables us to not only increase the position estimation rate but also bridge over possible brief GNSS outages. However, the position and attitude determined via this approach never correspond to the camera's EO, due to the physical displacement and misalignment of the GNSS antenna, IMU, and image sensor. This problem is tackled through inter-sensor calibration, a topic addressed within many research projects and also the author's publication included in this thesis (paper *Calibration and Accuracy Assessment in a Direct ...*).

The indirect technique is profitable mainly within those applications where high accuracy and reliability are required; researchers mostly report centimeter-level object accuracy even with uncalibrated (consumer-grade) cameras and fast-flying UASs. For example, *Barry and Coakley* presented the RMS object error rates of 2.3 and 3.5 cm in the XY plane and Z coordinate, respectively; the aerial data were acquired using a fixed-wing UAS flying at 90 m AGL (10 mm GSD) [40]. Similar results, 5.3 and 6.8 cm RMSE, respectively, were achieved by *Fazeli et al.* with a four-rotor UAS flying at 120 m AGL (24 mm GSD) [41] and by *Casella et al.*, who reported even sub-GSD accuracy, namely, 18 mm when flying at 70 m AGL [42]. Some of the present research outcomes render achievable accuracy approaching GSD level; however, the georeferencing quality depends on not only the accuracy of the GCPs but also the number and spatial distribution of these points. This topic previously embodied a topical issue in the context of manned photogrammetry [22] and still remains a problem of interest [43, 44].

Direct EO determination began to be discussed and examined at the turn of the millennium, given the increasing availability of GPS. The promising technology trend could be illustrated through the 1999 article *Direct Geocoding – is Aerial Triangulation Obsolete?* by M. Cramer [45], which assessed this method in the context of manned photogrammetry; however, other authors analyzed the topic too (e.g., J. Skaloud, M. Rehak) [46, 37, 47]. Nevertheless, meter or slightly sub-meter attainable accuracy could not compete with the traditional GCP-based approach in many applications.

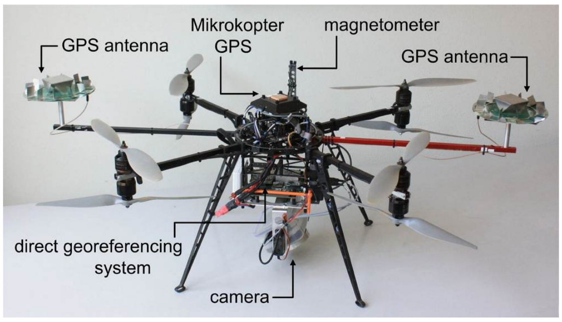
Multi-sensor integration for UAS remote sensing has embodied an openly discussed problem since the beginning of the 2010s, thanks to the wider availability of differential and PPK/RTK GNSSs and INSs with a reasonable size and pricing. This field involves many aspects; attention is paid to the system design and inter-sensor calibration, together with estimating the time delays, assessing the accuracy, and finding proper use cases. The calibration of the displacement and misalignment of individual sensors, namely, estimating the lever arms and boresight angles, is attainable in multiple ways, such as using laser scanning of the sensor system [48] or employing a close-range or in-situ calibration field to produce reference, aerial triangulation-based EO data [48, 49]. The latter technique is, in general, more suitable, but its reliability may be affected by a synchronization delay between the camera and the GNSS/INS. The delay is laboratory-determinable via a special tool allowing us to capture the exact time moment of the image acquisition with respect to the synchronization signal [50, 49]; alternatively, the task can be subjected to a comprehensive in-flight estimation procedure comprising multiple calibration parameters. In practice, any inaccurate synchronization translates the time error into an exterior orientation error [50].

At the time the author of this thesis started outlining his concept of a multi-sensor system, UASs integrating such technology were not commonly available, and relevant topics were discussed almost exclusively within research groups. Early multi-sensor integration for UASs had been proposed by *M. Nagai et al.* in 2009 [51]; in the project, a 300 kg helicopter was fitted with GPS/IMU and a stereo camera system to achieve decimeter-level georeferencing accuracy exploiting hybrid INS supported by bundle block adjustment. Accurate georeferencing utilizing a compact, eight-rotor flying platform was characterized in a 2012 paper published by *M. Blaha et al.* [52]. The post-processed, differential GPS increased the positioning accuracy by an order of magnitude; still, the decimeter-level accuracy did not meet the original expectations. Nevertheless, the presented technique for obtaining reference positioning data via a robotic total station may be considered an innovative solution. In the same year, another article demonstrated sub-meter image georeferencing accuracy in a UAS weighting less than 1 kg [53].

Integrating an RTK GNSS onto a micro UAS, a step necessary for increasing the georeferencing accuracy, was described within the 2012 paper by *M. Rieke et al.* [54] (Figure 2.2a). Even though the setup did not fulfill the original accuracy expectations, it addressed the fundamental problems associated with the approach, such as correction transmission or data synchronization. A comprehensive study was introduced by *M. Rehak* in 2013 [50]; the custom-built multi-rotor UAS equipped with an RTK GPS receiver and in-house INS was subjected to various calibration procedures, including those determining the camera's IO parameters, shutter lag, and lever arms. The preliminary results obtained by using a close-range calibration field indicated the possibility of attaining a centimeter-level image georeferencing accuracy; yet, real-world photogrammetry missions still need to be performed to determine the object point georeferencing quality. Very promising results were presented by *C. Eling et al.* in their 2015 study [49]; the multi-sensor system integrated a dual-antenna RTK GNSS receiver to provide not only the accurate position but also true-heading information to support attitude estimation (Figure 2.2b). Even though the presented georeferencing accuracy ranging within the centimeter level was achieved under close-to-ideal flight conditions (20 m AGL altitude, 2 m/s speed), the outcomes definitely suggest that the DG may possibly compete with the GCP-based approach. At that time, related topics were addressed by other researchers as well (e.g., [55, 56, 57, 58, 41]).

The aforementioned studies, all published relatively recently, indicate that the direct georeferencing technique in UAS photogrammetry is gaining in popularity among researchers and will likely become an alternative to the control point-based technique. Still, with respect to the high demands on the sensor system, its calibration, and inter-sensor

(a)



(b)

Figure 2.2.: An example of early experimental setups comprising multi-sensor systems for direct EO determination in UAS photogrammetry from 2012 (a) [54] and 2015 (b) [49].

synchronization, an overall improvement of the method's reliability poses a challenge to be addressed in the future. Moreover, most of the hitherto published results were obtained in almost ideal conditions; thus, the performance in real-word scenarios remains a factor to be analyzed in depth. Despite the fact that UAS photogrammetry has many aspects in common with its alternative branch practised via manned aircraft, certain characteristics, such as the ability to operate automatically or acquire products with superior resolution via low-altitude flying, open new possibilities for the future.

3. Research Summary

At the very beginning, the author's main research interest was within the development of a multi-rotor UAS intended to complete ATEROS (formerly known as CASSANDRA) [59, 60], a heterogeneous mobile robotic system developed by the Robotics and AI group headed by Prof. Zalud at Brno University of Technology. The central purpose of the multi-robot system rests in performing various reconnaissance and CBRNE missions via diverse terrestrial platforms. Robots from the Orpheus family, an underlying project designed to develop a four-wheel portable platform, have been utilized within various missions and experiments, such as those involving radiation mapping or water contamination measurement [61, 62]. Integrating the individual platforms into the ATEROS system allows the operator to control the robots remotely, by utilizing a uniform user interface, and to switch between them with regard to the actual needs of the mission; alternatively, some platforms are capable of performing certain mission tasks automatically, eliminating user interventions. To improve the system's overall usability, an aerial platform, a four-rotor UAS Uranus, was developed and integrated into ATEROS. These tasks constituted the author's main research aims until 2014; with respect to the expansion of unmanned systems, as discussed in the introduction, and also due to the increasing availability of suitable platforms on the market, the more recent aims and objectives shifted towards the application of UASs in environmental mapping and CBRNE robotics. More concretely in this context, increased emphasis was put on topics subsumed within ground control point-free aerial photogrammetry and, simultaneously, the utilization of the method in the discussed domains of robotics.

As the thesis stresses the author's selected publications, this section is intended to describe the context of the individual research outcomes and associated activities, together with those released through other papers not included herein. The results are also graphically summarized within Table 3.1.

The initial assignments in the discussed field mainly concerned the testing of the hardware components that allow us to directly determine the EO parameters; the components consisted in a carrier-phase measurement-enabled GNSS and an INS enabling the inclusion of external aiding data into the estimation process. The eventual sensor setup comprised a dual-antenna GNSS receiver that facilitated determining via the RTK technology not only the accurate position but also the true heading; such an approach was unusual within UASs at that time. By using several non-flight experiments, we validated the functionality of the concept and released the preliminary results at local conferences

2014/2015 • **Prior work**

Hardware components testing, designing sensor system, and performing initial non-flight and flight tests. Publishing the preliminary findings at local conferences.

2015/2016 • **Internship at Aalborg University (AAU)**

Obtaining new experiences in UAS and photogrammetry field, and conducting experiments with a fixed-wing UAS.

2016 • **Precise Multi-Sensor Georeferencing System for . . .**

Conference paper

Describing the multi-sensor system design and the results of the first test flight with the fully operable system.

2018 • **Calibration and Accuracy Assessment in a Direct . . .**

Journal article

Introducing a calibration procedure for the sensor system, and performing a comprehensive accuracy assessment.

2018 • **Cooperation Between an Unmanned Aerial Vehicle . . .**

Journal article

Designing a multi-robot procedure for a radiation source localization, and conducting tests utilizing previously obtained data.

2019 • **Towards Automatic UAS-Based Snow-Field . . .**

Journal article

Real condition system testing during the mapping of a snow cover depth in the Krkonose Mountains.

2020 • **Using an Automated Heterogeneous Robotic System . . .**

Submitted manuscript

Introducing a state-of-the-art multi-robot method for radiation surveys integrating both photogrammetry and radiation measurements, and performing a comprehensive experiment.

Table 3.1.: The timeline of the selected publications and related activities.

Figure 3.1.: The initial test flight with an early sensor system version showed the necessity of certain construction modification, but also verified the compatibility with UAS's hardware components (2015).

[63]. Still, these early publication outcomes pointed to the author's rather limited orientation in the photogrammetry field. The first UAS flight with a trial version of the sensor system was completed in 2015 (Figure 3.1), thanks to the supporting instrumentation from Mendel University in Brno. For the author, the lack of an unmanned platform embodied a considerable obstacle preventing faster development and testing cycles.

A worthwhile opportunity to foster the author's professional development consisted in the internship guaranteed by the department of *Automation and Control* at *Aalborg University*, where Assoc. Prof. A. la Cour-Harbo provided much of his valuable experience in drone research. The field testing with a fixed-wing UAS enabled the author to markedly expand his knowledge of photogrammetry and unmanned mission planning.

The fully operable multi-sensor system was initially published within a paper entitled *Precise Multi-Sensor Georeferencing System for Micro UAVs* [64], presented at *14th IFAC Conference on Programmable Devices and Embedded Systems* in 2016. The article comprises information about the sensor setup, test flight results, and ideas concerning the system calibration and time synchronization.

The calibration, namely, a procedure estimating the synchronization delay and the displacement and misalignment of the individual sensors, is of vital importance for achieving a high georeferencing accuracy. An in-flight calibration method employing aerial triangulation-based reference data to support the least-square estimation of the aforementioned calibration parameters was designed and then released in the *International Journal of Remote Sensing*[1] in 2018 through the article *Calibration and Accuracy Assessment in a Direct Georeferencing System for UAS Photogrammetry* [65]. This key publication addresses not only the calibration technique but also the overall verification of the system's performance via a comprehensive experiment confirming the reachability

[1]IF 2.49, Q2 in the *remote sensing* category, special issue titled *Unmanned Aerial Systems (UAS) for Environmental Applications*

of a centimeter-level object accuracy during a common UAS photogrammetry mission.

As the presented PhD research was motivated predominantly by the effort to find new opportunities for control point-free remote sensing in environmental mapping and tasks involving CBRNE threads, the next step rested in subjecting the technology to tests based on real-world scenarios. The subsequent paper entitled *Cooperation Between an Unmanned Aerial Vehicle and an Unmanned Ground Vehicle in Highly Accurate Localization of Gamma Radiation Hotspots* [66], published in the *International Journal of Advanced Robotic Systems*[2] in 2018, assessed the potential of cooperation between UASs and UGVs during radiation search missions. This application perfectly fits the *Robotics and AI* group scope, and the data collected within previous experiments were employed to design a procedure for highly automated radiation source localization.

The usability of the multi-sensor system was further verified within another real-word application: An experiment conducted in cooperation with the Krkonose Mountains National Park Administration demonstrated the benefits of the approach during an estimation of the snow field depth in a remote mountainous area. The elimination of ground controls reduces the field work required and the potential risks associated with avalanches. The task is thoroughly described in the article *Towards Automatic UAS-Based Snow-Field Monitoring for Microclimate Research* [67] published in *Sensors*[3] in 2019; this paper also addresses the workflow from the aerial imagery acquisition to the estimation of the snow field parameters.

Utilizing the findings presented within the above-mentioned paper on radiation search, we proposed a state-of-the-art procedure to facilitate highly automated multi-platform radiation surveys. The activities in the given field culminated with a comprehensive experiment to demonstrate the benefits of combining diverse robotic platforms to accomplish such a CBRNE task. Further, the design and use of a three-phase technique that involves aerial photogrammetry to enable aerial and terrestrial radiation mapping are the central topics of the manuscript *Using an Automated Heterogeneous Robotic System for Radiation Surveys* [68], which is currently being considered for publication (August 2020). Beyond the scope of this assignment, the author published two other conference papers analyzing UAS-based radiation mapping simulation [69, 70].

[2] IF 1.22, Q4 in the *robotics* category, special issue titled *Mobile Robots*

[3] IF 3.28, Q1 in the *instruments and instrumentation* category, special issue titled *UAV or Drones for Remote Sensing Applications in GPS/GNSS Enabled and GPS/GNSS Denied Environments*

4. Concluding Discussion

The results achieved within this Ph.D. research are classifiable into three areas corresponding to the original aims defined within the Aims and Objectives section. In this context, the initial efforts consisted in the development of the photogrammetric system for UASs, and due to certain circumstances, the outcome can be considered unique with respect to similar research pursued elsewhere at the time. As a suitable unmanned platform was unavailable to the author during the initial phases of the project, the adopted concept had to integrate all necessary components on a single rigid frame, making the system completely independent of the UAS. This approach generally enables the user to employ the system in different vehicles, without the need of recalibration; however, the actual usability is limited to multi-rotor UASs with a payload capacity of not less than 2.5 kg. The system's portability was verified via testing by various UAS operators, namely, Mendel University in Brno, the Krkonose Mountains National Park Administration, and the Military Technical Institute of the Czech Republic (Figure 4.1). The components integrated into the system represent the state of the art in the given segment, allowing us to attain a georeferencing accuracy at the same level as that known from GCP-based photogrammetry; moreover, the dual-antenna design to secure reliable attitude estimation constituted a pioneering solution within the UAS market.

Considering the different system calibration techniques published by other researchers, a custom-made procedure was designed to fulfill the specific requirements of the research. The proposed in-flight method estimates not only the geometric parameters, such as the displacement of the sensors, but also the synchronization delay. This embodies a step of vital importance, especially in systems involving consumer-grade sensors (for instance, digital cameras). While the calibration is supported by some photogrammetric softwares, its functionalities are limited to the lever arm estimation, omitting possible delay; this drawback then may cause poor accuracy in the results. Using the custom-made calibrating procedure to improve the georeferencing performance was assessed thoroughly by means of a test flight emulating a real-world photogrammetry mission. Although the outcomes indicate that the indirect method clearly outperforms the direct one, the object accuracy achieved (approx. 4 cm spatial RMS error at a GSD of 2 cm) fully satisfies the requirements of the above-defined applications in field robotics.

With respect to the extensive progress in UASs that was materialized during the last decade, the situation in the discussed field changed considerably, too. In view of the decreasing costs of crucial components, the carrier phase-enabled GNSS in particular,

(a) (b)

Figure 4.1.: The designed multi-sensor system was employed on different unmanned platforms: a DJI S800, in snow mapping (a), and a BRUS UAS, within a multi-robot radiation mapping experiment (b).

major UAS manufacturers introduced platforms allowing accurate georeferencing of aerial imagery (e.g., the SenseFly eBee plus, 2016; DJI Phantom 4 RTK, 2018; Yuneec H520 RTK, 2019; and DJI Matrice 300 RTK, 2020). Moreover, some of the products comprise a dual antenna RTK system to support attitude determination, an approach tested since 2014 by the author of this thesis. Even though the author's research appears to have been directed in an appropriate manner, as presently indicated by the trends in the commercial sphere, the room for further improvement is rather limited (due to precisely the multiple options available on the market); the interests and efforts to ensure further enhancement of the concept should thus be shifted towards tackling new tasks associated with the actual use of this technology.

Assessing the applicability of the sensor system in both real-world scenarios involving CBRNE robotics and environmental mapping embodied a vital part of the project. In this context, two distinct processes were addressed, namely, snow cover mapping in mountainous regions and radiation search. Considering the former of these two tasks, the usefulness of the system was verified via cooperation with the Krkonose Mountains National Park Administration, a joint activity to estimate the snow depth at a prominent snow field (Mapa republiky). The technology met the expectations as regards eliminating the safety risks related to the usage of GCPs, and the attained accuracy satisfied the requirements for the given assignment. Still, assuming the actual conditions, utilizing several check points is recommendable to increase the overall reliability of the mapping products.

The latter area examined, robotic radiation mapping and source localization, was analyzed thoroughly within several conference and journal articles, and the results obtained during the simulations and experiments may be regarded as reaching beyond the state of the art in this field. The control point free photogrammetry proved to be a key method to provide updated and accurate maps of regions comprising CBRNE risks; the products enabled us, above all, to solve the path planning problems connected with the diverse robotic platforms employed to fulfill the radiation mapping tasks.

Although the comprehensive technique for multi-robot mapping described in the last of the papers within the thesis was designed to eliminate human operators as much as possible, the current trends in robotics are towards real-time data processing, allowing us to reach an even higher level of autonomy. In applications where the absolute accuracy of mapping products does not stand at the forefront of the efforts, simultaneous localization and mapping (SLAM), together with data-driven mission planning, may change the mapping process markedly, paving the way for fully autonomous systems. Such approaches embody a suitable options for employing robots in GNSS-denied environments, or speeding-up threat's localization during CBRNE missions. Still, UAS photogrammetry as interpreted in this thesis will certainly become a standard tool within diverse fields in the future, especially in those applications, where GIS embodies a standard processing tool.

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Part II.

Publications

A. Precise Multi-Sensor Georeferencing System for Micro UAVs

Bibliographic Information

GABRLIK, Petr, Ales JELINEK and Premysl JANATA. Precise Multi-Sensor Georeferencing System for Micro UAVs. In: *IFAC-PapersOnLine* [online]. Cham: Elsevier, 2016, pp. 170–175 [cit. 2020-08-25]. DOI: 10.1016/j.ifacol.2016.12.029. ISSN 2405-8963. Available from: `https://linkinghub.elsevier.com/retrieve/pii/S2405896316326659`

Abstract

In aerial photogrammetry, the direct georeferencing technique using micro Unmanned Aerial Vehicles (UAVs) is generally used less frequently than the indirect approach, especially due to the intensive calibration and equipment-related requirements. Conversely, this technique offers several advantages which can be beneficial in some applications. This paper discusses the development and testing of a precise multi-sensor system for the direct georeferencing of aerial imagery. The system comprises a dual-antenna Real Time Kinematic (RTK) Global Navigation Satellite System (GNSS) receiver with a centimeter level accuracy and an Inertial Navigation System (INS), which fuses inertial and position information to provide accurate navigation and orientation data in real time. Special attention is paid to the time synchronization of various sensor data and lever arm correction. The 3D print technology was applied to ensure low weight and high modularity of the system, which can be easily modified and mounted to different types of UAVs. The paper also describes a test flight mission and the processing workflow, from the data acquisition to the import of the georeferenced orthophoto to a Geographic Information System (GIS).

Author's Contribution

The author designed and constructed a significant part of the presented system, analyzed related research, participated in the experiments, and processed the results. He also wrote the manuscript independently and contributed to its finalization.

Author contribution: 85 %

Acknowledgement

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B. Calibration and Accuracy Assessment in a Direct Georeferencing System for UAS Photogrammetry

Bibliographic Information

GABRLIK, Petr, Anders la COUR-HARBO, Petra KALVODOVA, Ludek ZALUD and Premysl JANATA. Calibration and accuracy assessment in a direct georeferencing system for UAS photogrammetry. *International Journal of Remote Sensing* [online]. 2018, **39**(15–16), 4931–4959 [cit. 2020-08-25]. DOI: 10.1080/01431161.2018.1434331. ISSN 0143-1161. Available from: `https://www.tandfonline.com/doi/full/10.1080/01431161.2018.1434331`

Abstract

Unmanned aerial systems (UAS) have already proven useful in fields and disciplines such as agriculture, forestry, or environmental mapping, and they have also found application during natural and nuclear disasters. In many cases, the environment is inaccessible or dangerous for a human being, meaning that the widely used technique of aerial imagery georeferencing via ground control points cannot be employed. The present paper introduces a custom-built multi-sensor system for direct georeferencing, a concept that enables georeferencing to be performed without an access to the mapping area and ensures centimetre-level object accuracy. The proposed system comprises leading navigation system technologies in the weight category of micro and light UASs. A highly accurate global navigation satellite system receiver integrating the real time kinematic technology supports an inertial navigation system where data from various sensors are fused. Special attention is paid to the time synchronisation of all sensors, and a method for the field calibration of the system is designed. The multi-sensor system is completely independent of the used UAS.

The authors also discuss the verification of the proposed system's performance on a real mission. To make the results credible, a high number of test points are used, with both

the direct and the indirect georeferencing techniques subjected to comparison, together with different calibration methods. The achieved spatial object accuracy (about 4 cm RMSE) is sufficient for most applications.

Author's Contribution

The author surveyed and reviewed related research, designed the calibration method, participated in the testing of the system, and processed the results. He was also exclusively responsible for writing the manuscript and contributed to its finalization.

Author contribution: 80 %

Acknowledgement

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C. Cooperation Between an Unmanned Aerial Vehicle and an Unmanned Ground Vehicle in Highly Accurate Localization of Gamma Radiation Hotspots

Bibliographic Information

LAZNA, Tomas, Petr GABRLIK, Tomas JILEK and Ludek ZALUD. Cooperation between an unmanned aerial vehicle and an unmanned ground vehicle in highly accurate localization of gamma radiation hotspots. *International Journal of Advanced Robotic Systems* [online]. 2018, **15**(1), 1–16 [cit. 2020-08-25]. DOI: 10.1177/1729881417750787. ISSN 1729-8814. Available from: http://journals.sagepub.com/doi/10.1177/1729881417750787

Abstract

The paper discusses the highly autonomous robotic search and localization of radiation sources in outdoor environments. The cooperation between a human operator, an unmanned aerial vehicle (UAV), and an unmanned ground vehicle (UGV) is used to render the given mission highly effective, in accordance with the idea that the search for potential radiation sources should be fast, precise, and reliable. Each of the components assumes its own role in the mission; the UAV (in our case, a multirotor) is responsible for fast data acquisition to create an accurate orthophoto and terrain map of the zone of interest. Aerial imagery is georeferenced directly, using an onboard sensor system, and no ground markers are required. The UAV can also perform rough radiation measurement, if necessary. Since the map contains 3D information about the environment, algorithms to compute the spatial gradient, which represents the rideability, can be designed. Based on the primary aerial map, the human operator defines the area of interest to be examined by the applied UGV carrying highly sensitive gamma-radiation probe/probes. As the actual survey typically embodies the most time-consuming problem within the mission,

major emphasis is put on optimizing the UGV trajectory planning; however, the dual-probe (differential) approach to facilitate directional sensitivity also finds use in the given context. The UGV path planning from the pre-mission position to the center of the area of interest is carried out in the automated mode, similarly to the previously mentioned steps.

Although the human operator remains indispensable, most of the tasks are performed autonomously, thus substantially reducing the load on the operator to enable them to focus on other actions during the search mission. Although gamma radiation is used as the demonstrator, most of the proposed algorithms and tasks are applicable on a markedly wider basis, including, for example, chemical, biological, radiological, and nuclear missions and environmental measurement tasks.

Author's Contribution

The author was responsible primarily for the tasks related to the aerial system, namely, the mission planning, aerial data acquisition, and relevant processing. Moreover, he was involved in designing the method and interpreting the results; thus, he wrote the sections UAV and Aerial Mapping and significantly contributed to the Introduction, Process Description, Discussion and Conclusion chapters. The author is also credited with finalizing the manuscript

Author contribution: 30 %

Acknowledgement

This work was supported by the European Regional Development Fund under the project Robotics 4 Industry 4.0 (reg. no. CZ.02.1.01/0.0/0.0/15_003/0000470).

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D. Towards Automatic UAS-Based Snow-Field Monitoring for Microclimate Research

Bibliographic Information

GABRLIK, Petr, Premysl JANATA, Ludek ZALUD and Josef HARCARIK. Towards Automatic UAS-Based Snow-Field Monitoring for Microclimate Research. *Sensors* [online]. 2019, **19**(8), 1–23 [cit. 2020-08-25]. DOI: 10.3390/s19081945. ISSN 1424-8220. Available from: https://www.mdpi.com/1424-8220/19/8/1945

Abstract

This article presents unmanned aerial system (UAS)-based photogrammetry as an efficient method for the estimation of snow-field parameters, including snow depth, volume, and snow-covered area. Unlike similar studies employing UASs, this method benefits from the rapid development of compact, high-accuracy global navigation satellite system (GNSS) receivers. Our custom-built, multi-sensor system for UAS photogrammetry facilitates attaining centimeter- to decimeter-level object accuracy without deploying ground control points; this technique is generally known as direct georeferencing. The method was demonstrated at Mapa Republiky, a snow field located in the Krkonose, a mountain range in the Czech Republic. The location has attracted the interest of scientists due to its specific characteristics; multiple approaches to snow-field parameter estimation have thus been employed in that area to date. According to the results achieved within this study, the proposed method can be considered the optimum solution since it not only attains superior density and spatial object accuracy (approximately one decimeter) but also significantly reduces the data collection time and, above all, eliminates field work to markedly reduce the health risks associated with avalanches.

Author's Contribution

The author contributed extensively to all parts of the article. He surveyed and analyzed related research and was the principal participant in designing the method, preparing the experiment, ensuring the field activities, processing the data, and interpreting the results. Moreover, the author was exclusively responsible for the writing the manuscript and is credited with finalizing the text.

Author contribution: 90 %

Acknowledgement

This work was supported by the European Regional Development Fund under the project Robotics for Industry 4.0 (reg. no. CZ.02.1.01/0.0/0.0/15_003/0000470).

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E. Using an Automated Heterogeneous Robotic System for Radiation Surveys

Bibliographic Information

GABRLIK, Petr, Tomas LAZNA, Tomas JILEK, Petr SLADEK a Ludek ZALUD. Using an Automated Heterogeneous Robotic System for Radiation Surveys. Manuscript submitted for publication. Available from: `https://arxiv.org/abs/2006.16066`

Abstract

During missions involving radiation exposure, unmanned robotic platforms may embody a valuable tool, especially thanks to their capability of replacing human operators in certain tasks to eliminate the health risks associated with such an environment. Moreover, rapid development of the technology allows us to increase the automation rate, making the human operator generally less important within the entire process. This article presents a multi-robotic system designed for highly automated radiation mapping and source localization. Our approach includes a three-phase procedure comprising sequential deployment of two diverse platforms, namely, an unmanned aircraft system (UAS) and an unmanned ground vehicle (UGV), to perform aerial photogrammetry, aerial radiation mapping, and terrestrial radiation mapping. The central idea is to produce a sparse dose rate map of the entire study site via the UAS and, subsequently, to perform detailed UGV-based mapping in limited radiation-contaminated regions. To accomplish these tasks, we designed numerous methods and data processing algorithms to facilitate, for example, digital elevation model (DEM)-based terrain following for the UAS, automatic selection of the regions of interest, obstacle map-based UGV trajectory planning, and source localization. The overall usability of the multi-robotic system was demonstrated by means of a one-day, authentic experiment, namely, a fictitious car accident including the loss of several radiation sources. The ability of the system to localize radiation hotspots and individual sources has been verified.

Author's Contribution

The author was responsible primarily for the tasks related to the aerial system, namely, the mission planning, aerial data acquisition, and relevant processing. Furthermore, he significantly contributed to surveying and analyzing related research, designing the method, and interpreting the results; the author is also credited with writing parts of the manuscript.

Author contribution: 30 %

Acknowledgement

The research was supported by European Regional Development Fund under the project Robotics 4 Industry 4.0 (reg. no. CZ.02.1.01/0.0/0.0/15_003/0000470). Further funding was provided via the National Center of Competence 1 program of the Technology Agency of the Czech Republic, under the project TN01000024/15 "Robotic operations in a hazardous environment and intelligent maintenance".

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This is a submitted version of the manuscript; the fulltext is also available at the *arXiv* preprint server: `https://arxiv.org/abs/2006.16066`.

Part III.

Appendices

A. List of Author's Publications

Journal Articles With Impact Factor

GABRLIK, Petr, Premysl JANATA, Ludek ZALUD and Josef HARCARIK, Josef. Towards Automatic UAS-Based Snow-Field Monitoring for Microclimate Research. *Sensors* [online]. 2019, **19**(8), 1–23 [cit. 2020-08-25]. DOI: 10.3390/s19081945. ISSN 1424-8220. Available from: `https://www.mdpi.com/1424-8220/19/8/1945`

GABRLIK, Petr, Anders la COUR-HARBO, Petra KALVODOVA, Ludek ZALUD and Premysl JANATA. Calibration and accuracy assessment in a direct georeferencing system for UAS photogrammetry. *International Journal of Remote Sensing* [online]. 2018, **39**(15–16), 4931–4959 [cit. 2020-08-25]. DOI: 10.1080/01431161.2018.1434331. ISSN 0143-1161. Available from: `https://www.tandfonline.com/doi/full/10.1080/01431161.2018.1434331`

LAZNA, Tomas, Petr GABRLIK, Tomas JILEK and Ludek ZALUD. Cooperation between an unmanned aerial vehicle and an unmanned ground vehicle in highly accurate localization of gamma radiation hotspots. *International Journal of Advanced Robotic Systems* [online]. 2018, **15**(1), 1–16 [cit. 2020-08-25]. DOI: 10.1177/1729881417750787. ISSN 1729-8814. Available from: `http://journals.sagepub.com/doi/10.1177/1729881417750787`

Scopus/WoS Indexed Articles

LAZNA, Tomas, Petr GABRLIK, Tomas JILEK and Frantisek BURIAN. Simulating UAS-Based Radiation Mapping on a Building Surface. In: *Modelling and Simulation for Autonomous Systems* [online]. Cham: Springer, 2020, pp. 130–147 [cit. 2020-08-25]. Lecture Notes in Computer Science, 11995. DOI: 10.1007/978-3-030-43890-6_11. ISBN 978-3-030-43889-0. Available from: `http://link.springer.com/10.1007/978-3-030-43890-6_11`

GABRLIK, Petr. Boresight Calibration of a Multi-Sensor System for UAS Photogrammetry. In: *2018 ELEKTRO* [online]. Piscataway (NJ): IEEE, 2018, pp. 1–6 [cit. 2020-08-25]. DOI: 10.1109/ELEKTRO.2018.8398362. ISBN 978-1-5386-4759-2. Available from: `https://ieeexplore.ieee.org/document/8398362/`

GABRLIK, Petr and Tomas LAZNA. Simulation of Gamma Radiation Mapping Using an Unmanned Aerial System. In: *IFAC-PapersOnLine* [online]. Amsterdam: Elsevier, 2018, pp. 256–262 [cit. 2020-08-25]. DOI: 10.1016/j.ifacol.2018.07.163. ISSN 2405-8963. Available from: `https://linkinghub.elsevier.com/retrieve/pii/S2405896318309091`

LAZNA, Tomas, Tomas JILEK, Petr GABRLIK and Ludek ZALUD. Multi-robotic Area Exploration for Environmental Protection. In: *Industrial Applications of Holonic and Multi-Agent Systems* [online]. Cham: Springer, 2017, pp. 240–254 [cit. 2020-08-25]. Lecture Notes in Computer Science, 10444. DOI: 10.1007/978-3-319-64635-0_18. ISBN 978-3-319-64635-0. ISSN 1611-3349. Available from: `http://link.springer.com/10.1007/978-3-319-64635-0_18`

GABRLIK, Petr, Ales JELINEK and Premysl JANATA. Precise Multi-Sensor Georeferencing System for Micro UAVs. In: *IFAC-PapersOnLine* [online]. Cham: Elsevier, 2016, pp. 170–175 [cit. 2020-08-25]. DOI: 10.1016/j.ifacol.2016.12.029. ISSN 2405-8963. Available from: `https://linkinghub.elsevier.com/retrieve/pii/S2405896316326659`

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