TECHNICAL AND ANALYTICAL CHALLENGES INVOLVED IN DRONE-BASED LASER-INDUCED BREAKDOWN SPECTROSCOPY MEASUREMENTS FOR SECURITY APPLICATIONS

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Abstract
This presentation overviews the process of the development of drone-based LIBS instrumentation meant to be used primarily in security applications. We explain the difficulties faced and the potential solutions devised to tackle them. We also share our first results obtained during laboratory-based and field measurments with the system.

Introduction
Laser-induced breakdown spectroscopy (LIBS) is a versatile analytical laser spectroscopy method, which uses a focused laser beam to produce a microplasma on the surface (or inside) of a target and observes and the light emitted by the plasma to reveal the chemical composition of the target (sample). The instrument can be made fairly compact and robust, considering that its main components are some optical elements (focusing and light collection optics), a pulsed and intense laser source, a spectrometer and some synchronization electronics. From an analytical point of view, LIBS offers uniquely advantageous features which can be exploited in multiple ways in industrial, security or scientific applications [1, 2]. Among these features, trace analytical sensitivity, very short measurement times, high information content in the collected dataset, field-based or stand-off measurement capabilities are perhaps the most important for security-related applications. Several successful related analytical demonstrations were already described in the scientific literature, including e.g. the stand-off detection of explosives [3], biological aerosols [4], nuclear materials [5], etc.

Along with the rapid development of ultracompact unmanned aerial vehicles (UAV, commonly referred to as “drones”) laser spectroscopy researchers started to explore the possibility to construct and use drone-based compact LIBS instruments [6], which would provide ultimate flexibility in security applications. Our pilot research projects financed by NKFIH (Hungary) aiming at demonstrating the potential of LIBS spectroscopy in chemical, biological, radiological, and nuclear CBRN) security applications also belong to these efforts. The current paper describes the challenges involved in the realization of such a device and outlines our preliminary results related to specific applications.

Experimental
All LIBS experiments were performed using an in-house developed measurement system. This system is built around a GigaRotor6 type industrial-grade hexacopter drone and a LIBS setup whose main components are a compact, solid-state pulsed laser and a Nexos (Avantes, NL) fiber optic CCD spectrometer. For target distance measurements purposes, a Banner LT3 laser

distance sensor was incorporated. Communication, data storage and control functions were programmed in Python, and the program was run on a Raspberry Pi model 5 microcomputer.

Figure 1. System components, from left to right: hexacopter drone, compact fiber optic spectrometer, laser distance meter

Results and discussion

Our approach during the R&D project involved the following steps: *1)* define/specify the analytical goal (application, expected performance) of the system, *2)* identify the challenges and potential solutions involved, also considering operational safety and the capabilities of state-of-the-art industrial drones, *3)* construct the system, *4)* perform pilot measurements. In this abstract and in our presentation, we give a brief account of the results of all these steps.

Specifications. A drone-based pilot LIBS system should be considered as a remotely-controlled chemical sensor. Visually-driven human guidance is needed to spot a potential target and then initiate an analytical inspection to assess the chemical identity or composition of the target (sample). In later phases of the project, autonomous system operation may be imagined. Although stand-off LIBS measurements were already successfully demonstrated in the laboratory, but the challenges outlined below dictate that the drone-sample distance should be limited to a few meters. A LIBS analytical measurement only takes a fraction of a millisecond, the instrumentation is compact, lightweight (max. a few kg) and consumes small electrical power (ca. 50-100 W). Considering the operational distance, the necessity to record atomic spectra and the requirements for cost-efficiency and compactness, the system should incorporate a nanosecond laser source and a high resolution (around 0.1 nm), fiber-optic coupled CCD or CMOS spectrometer working in the UV-Vis range.

Challenges and solutions. Analytical, technical and operational safety issues are strongly interrelated. The following table attempts to give an overview of the most important aspects. Discussion of most challenges would exceed the limits of this abstract, therefore we only discuss a few here. For example, drone maneuvering accuracy and positional stability should be a high priority, given the very small analytical spot of LIBS. Vibrations and small movements should not be a problem though, given the very short measurement time. GPS-driven drone movement control is out of the question, as GPS accuracy is orders of magnitude poorer (e.g. 1 m) than what is required (ca. 1 mm). For less demanding applications, drone height (above ground distance) can be calculated by the barometric formula or by GPS, but it has a couple of meters accuracy only, and this is inacceptable for LIBS, where the target distance needs to be known/controlled with few mm accuracy. Only laser-guided distance measurements (e.g. laser pulse time-of-light measurements) are capable to provide both the height and directional (aiming) accuracy needed here.

In terms of safety, the issues are mostly drone-related, general ones. However, there is a couple of issues which are associated with the use of a pulsed, intense laser beam in the open field. With respect to these, one countermeasure that must be implemented is that the laser is only turned on when a measurement is initiated and the drone is not directed to move (is supposed to be in a stable hover), this can be achieved by using an electromagnetic (or maybe electrooptical) safety interlock. In order to avoid (limit) any injuries or damages caused by joltlike, unintentional drone movements while measuring, the implementation of another safety switch can be suggested: this could be a tilt sensor, which can quickly shut the laser down (block the laser path) if the tilt of the drone exceeds a preset limit (please note that the laser beam is pointing vertically downwards under normal circumstances, thereby potential harm can only be done if the drone is excessively tilted). Last, but not least, the system should also be able to recognize if a human (or animal) is present directly under the drone. This feature can be implemented by using a shape recognition software working, in real time, on the camera data stream ("smart camera").

Table 1. An overview of some of the most important challenges concerning drone-based LIBS systems

Analytical challenges (LIBS-centered)	**Technical challenges (drone-centered)**	**Safety issues**
• increasing operational distance decreases sensitivity • dust particles, humidity, gases and turbulence in the optical path can have an influence on the performance • the higher the resolution of the spectrometer, the lower is the sensitivity • the broader is the spectral coverage, the lower is the resolution and sensitivity • aiming should have a high positional accuracy (mm-range) • laser wavelength should be not interfering with spectrometer • tilted target surfaces will decrease sensitivity	• sufficient load-carrying capacity • sufficient electrical power to subsystems • high maneuvering accuracy (positional control) is needed in the x-y plane • a continuous, high accuracy (mm) monitoring of drone-target distance is required • a continuous feed of imaging data is necessary to the operator • rotors generate dust and wind (turbulance) which dictates longer operational distances • on-board evaluation capability or high-speed streaming for measurement data (spectra + images) is needed • communication range	• danger of laser-inflicted eye or skin injuries to persons in the measurement path or caused by tilted, reflective targets • danger of laser-induced fire, explosions or release of CBRN materials • danger of rotor-inflicted damages to installations or injuries of persons in the measurement path • fall-inflicted damages to installations or injuries of persons in the measurement path, caused by drone failure/out-of-communication/out-of-power/EMI situations

Construction. The LIBS measurement module was built inside a plastic box (600×600×200 mm) attached to the bottom of the drone (in between the legs propping up the drone when standing on the ground). Fiber optic cables and a combination of reflective and transmissive optical elements were employed in the focusing and light collection optics. A compact, 532 nm laser was chosen as the excitation source, and the spectrometer was configured to measure in the 380-470 nm spectral range. The target distance is continuously monitored by a laser distance sensor which is aiming at the same spot as the excitation laser beam.

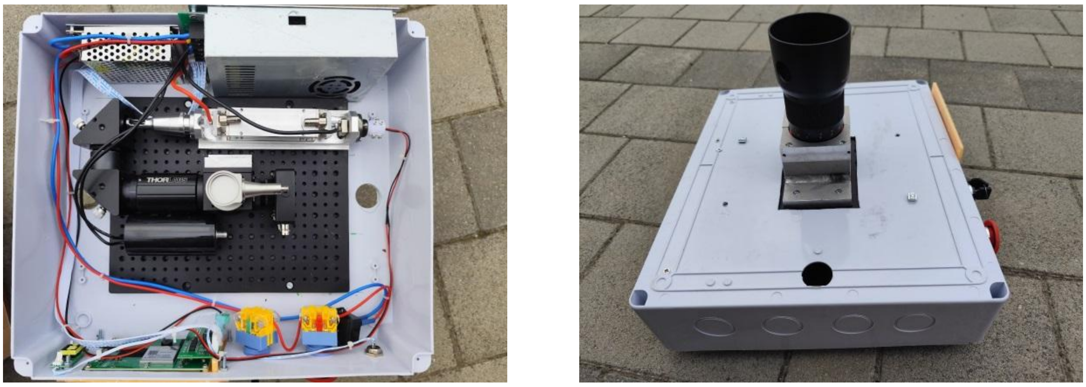

Figure 2. Photos of the internal system assembly (left) and the optics (right).

Measurements. The operational sequence of the system is the following. The operator steers the system over the target (suspicious object), at a height which is larger than the measurement distance. The target is locked by the operator and the drone enters a hovering mode, with no (intentional) lateral movements. The drone is then slowly lowered while the target distance is continuously monitored. At the moment when the target distance is equal to the measurement distance (set by the LIBS optics), the laser is fired, and the target's emission atomic spectrum is captured. This spectrum is time and position stamped and is wirelessly streamed down to the operator's computer along with the GPS coordinates and the camera image taken at the same moment when the laser is fired. In the presentation, we will also share some LIBS spectra collected with our system. Fertilizers and other metal salts were used as test samples.

Conclusion

We made significant steps towards the development of a functional drone-based LIBS measurement system. We assessed the technical and analytical challenges associated with the development and navigated them. Finally, we constructed a pilot system with which demonstrative field experiments were performed.

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