Expanding Horizons: Introducing a 6-Channel VNIR-SWIR Multicamera System for Advanced UAV-based Remote Sensing Applications

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Abstract: In 2019, we introduced a novel VNIR-SWIR multi-camera system for UAV-based SWIR spectral imaging, making narrowband 2D spectral image data more accessible for agricultural field analysis. Despite its success and robust performance, it faced limitations, such as the need for multiple flights for comprehensive spectral captures. To address these shortcomings, we have developed a new 6-channel VNIR-SWIR multi-camera system that leverages the latest InGaAs camera modules and embedded technology. This advanced system is lighter and offers six channels with four times the resolution of the former. Its use is expected to further advance UAV-based SWIR remote sensing, starting with field validations and extensive data collection planned for the upcoming growing season.

1 Introduction and Motivation

In the steadily evolving field of UAV-based remote sensing, the short-wave infrared (SWIR) domain, which spans wavelengths from approximately 1000 to 2700 nm, offers a unique perspective on vegetation (ROBERTS et al. 2018; CIMTAY et al. 2021; BERGER et al. 2022). This spectral range is potentially crucial for applications such as precision agriculture, forest management, and environmental monitoring, where in-depth vegetation analysis is essential for sustainable decision making (BERGER et al. 2020; OLIVEIRA et al. 2023).

Historically, the adoption of SWIR technology in UAV-based remote sensing has been limited and predominantly utilized in hyperspectral imaging systems and airborne spectroradiometers (ARROYO-MORA et al. 2021; TURNER et al. 2023). The mainstream application of multi-camera systems for vegetation monitoring has primarily focused on the visible (VIS) and near-infrared (NIR) domains (AASEN et al. 2018). This is attributed to the ease of utilizing conventional silicon imaging sensors for wavelengths below 1000 nm (HERRMANN et al. 2010). In contrast, the detection of the electromagnetic spectrum above 1000 nm necessitates the use of sensors made from composite materials, such as indium gallium arsenide (InGaAs), in different mixing proportions, depending on the wavelength range, that is, 1000-1700 nm or 1700-2500 nm, in which they are intended to be used (WANG et al. 2019). This requires a highly specialized manufacturing process, which is coupled with smaller production volumes, resulting in significant challenges, notably, higher raw material costs and sourcing constraints, a higher rate of production rejection, and a reliance on small-batch production, leading to higher costs compared to silicon-based sensors.

Moreover, due to the subsequently required complex interface technologies of these InGaAs pixel arrays, the resulting modules have been notably bulky, voluminous, and energy-intensive. These limitations have made the integration of such sensors into lightweight, multi-camera

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UAV systems exceedingly impossible for a long time. This originates from the fact that SWIR sensors have traditionally been limited to niche military applications, dominated by a few industry players, such as SCD, Sensors Unlimited, and Teledyne FLIR, often subsidiaries of defense companies. Initially developed for strategic military purposes with government support, infrared sensors in general are heavily regulated under dual-use policies. These international regulations naturally complicate imports and exports, which also affects ready-made camera products with these sensors. Especially for scientific field campaigns abroad, that is, outside the EU, with infrared-capable camera systems, sufficient lead time must always be considered to obtain the corresponding export license from the responsible national authorities, such as the Federal Office of Economics and Export Control (BAFA) in Germany.

However, the landscape of SWIR image sensors is undergoing transformation and has changed fundamentally. The growing integration of SWIR technology in the automotive and food industries, particularly in advanced driver assistance, food inspection, and filling systems, has catalyzed the demand for SWIR sensors (ELECTRONICSWORLD 2023). This increase in demand stimulates the development of mass-produced, cost-effective InGaAs sensors, which gradually reduces costs (EETIMES 2022). Although still more expensive than silicon sensors, the price gap is narrowing, signaling a potential rise in the adoption of the advantages of SWIR technology. This is also reflected in a significant shift, as leading consumer imaging companies such as Sony have entered the SWIR sector driven by OEM demand for innovative integration applications. In this way, decades of experience are being used to develop new production techniques and concepts, striving to overcome the production challenges of the past and make SWIR sensors economically viable for the mass market (YOLEGROUP 2023).

This shift in the SWIR sensor market is promising not only for traditional InGaAs sensors, but also for emerging technologies such as quantum dot focal planes. These technological advancements could lead to their incorporation into future multi-camera systems, expanding the potential use of image-based SWIR sensors in various remote sensing fields to the cost of their silicon-based counterparts.

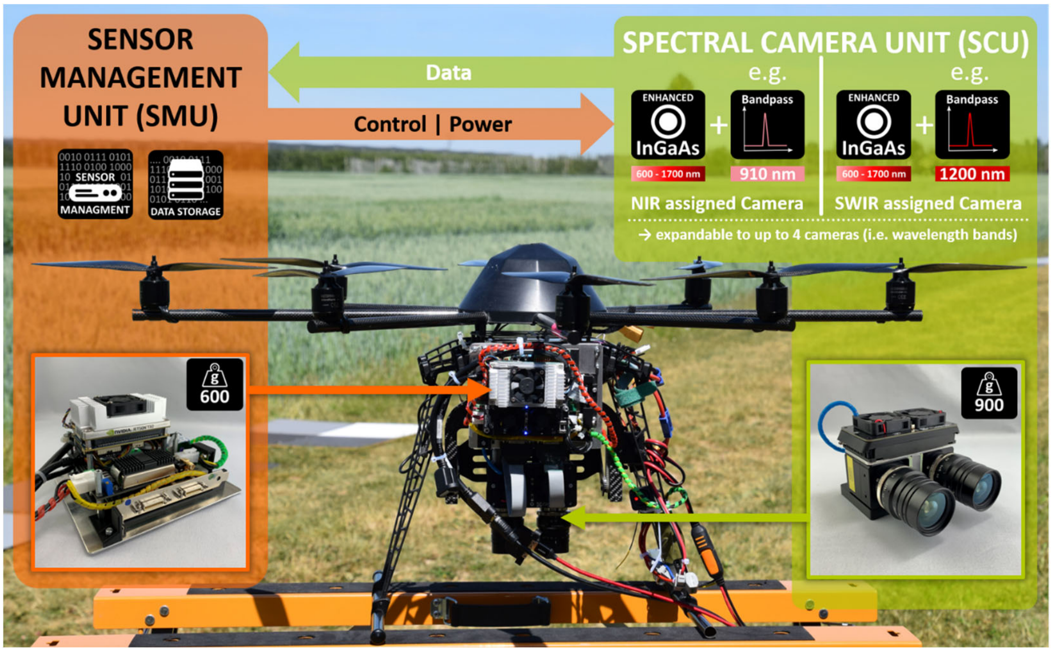

Fig. 1: Overview of the initial version of the modular concept of the VSWIR multi-camera system developed at the beginning of 2019 (JENAL et al. 2021)

In 2019, our team developed a pioneering dual-band VNIR-SWIR 2D multi-camera system specialized for UAV applications, as shown in Fig. 1 (JENAL et al. 2019). Due to the lack of available embedded technology, the system was built using standard industrial cameras which, to this date, were cutting-edge enhanced InGaAs sensors (600 to 1700 nm) optimized for Size, Weight, and Power (SWaP). Due to the housing and interface technology, it was not possible to realize the smallest possible design; therefore, a fairly modular system was created consisting of a control unit and a camera unit. This innovative approach allowed for the first documented simultaneous capture of 2D images at multiple narrowband SWIR wavelengths using frame sensors, enhancing the quality and efficiency of vegetation monitoring beyond 1000 nm. The ability of the system to acquire detailed spectral data in parallel over extensive agricultural fields has marked a substantial advancement in the field, possibly allowing for more nuanced and rapid assessments of crop traits, disease detection, and species identification (JENAL et al. 2020, JENAL et al. 2021). Moreover, two-dimensional image data allow for straightforward image processing in structure-from-motion (SfM) workflows. During several field campaigns, the system was steadily improved, and when possible, existing components were replaced by new, more sophisticated ones, such as smaller frame grabber hardware (Fig. 2). The last major overhaul was made at the beginning of 2023, in preparation for an extended field trip to the Atacama Desert. For this purpose, the modular camera system could be easily customized into a UAV-based multimodal sensor rig. It had to be completely encapsulated to protect the hardware against harsh environments, such as dust exposure, and to guarantee better thermal management (Fig. 3).

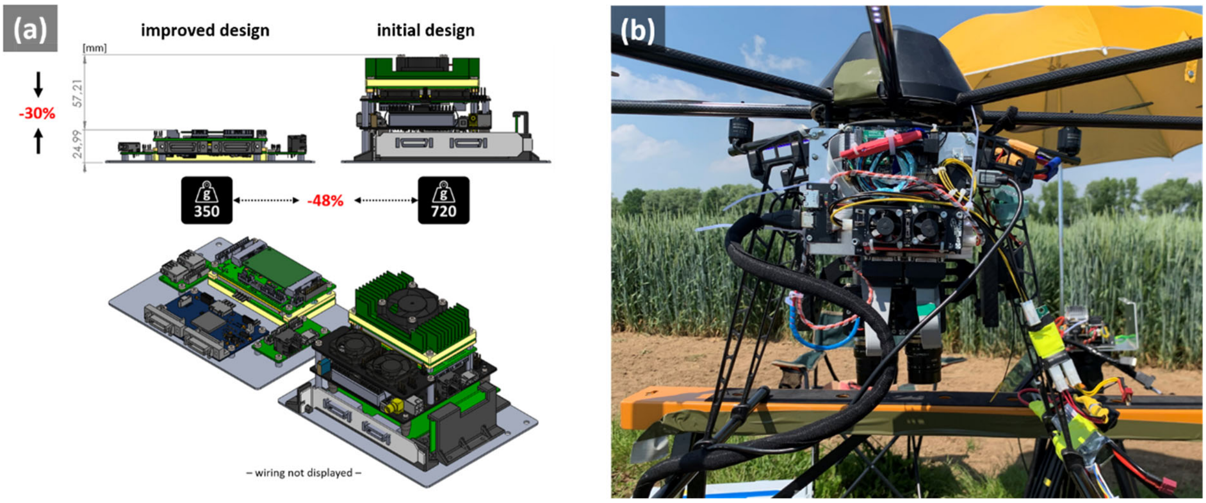

Fig. 2: **(a)** Visualization of the improvement in switching to the latest frame grabber hardware from the old two-band system. **(b)** Using the improved VSWIR multi-camera system during a field campaign 2021 in an experimental field for winter wheat

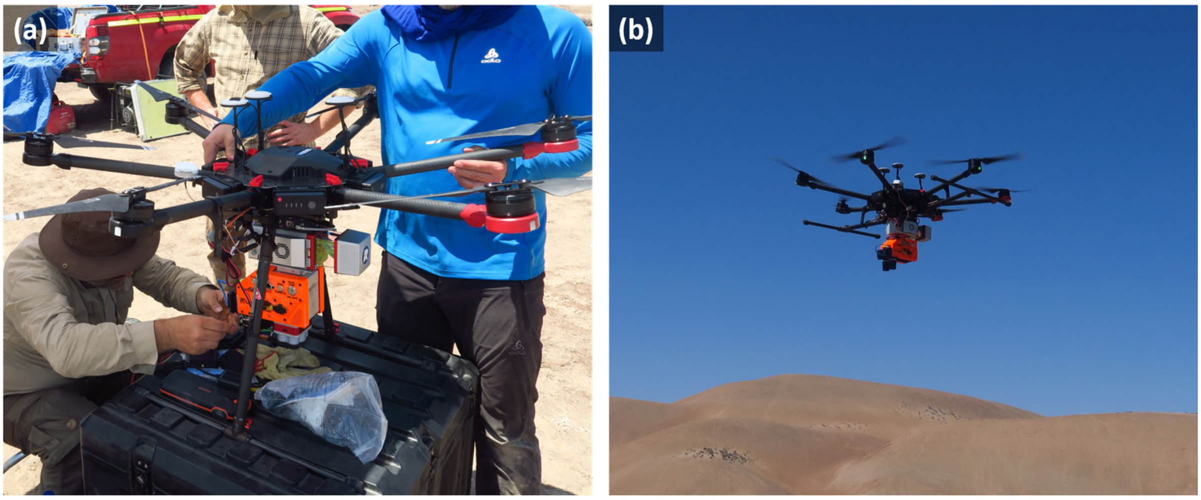

Fig. 3: **(a)** Preflight preparations of a multisensor survey in the Atacama Desert. Here, the VSWIR multi-camera system was flown in combination with a LiDAR and a VIS-NIR multi-camera system. **(b)** SWIR multi-camera system and LiDAR scanner in operation on a UVA. The VIS-NIR imager was unmounted after the first flight to reduce take-off weight

Despite its success and all the improvements, the original system faced challenges that could not be overcome with existing hardware. In particular, the need for successive flights and filter changes to capture more than two spatially high-resolution spectral bands has been the most significant disadvantage to date. In the worst-case scenario, the filter change procedure can lead to a temporal offset of the recorded data, which, despite extensive calibration, did not always result in consistent data sets under rapidly changing illumination conditions. Replacing the filter flanges during the field campaign also carries the risk of contamination by dust particles and dirt of all types and, ultimately, possible damage to the sensor. This requires careful handling of the camera system and cannot be taught to different users without intensive training.

Recognizing the limitations and being driven by the rapid technological advancements in sensor technology and computational power, we embarked on a comprehensive redesign. The requirements for such a system redesign were correspondingly high. For example, more than two channels with, at best, a higher spatial sensor resolution had to be integrated into the system. Six channels have been proven to be realistically feasible here. This also corresponds to the current number of recorded channels with the old system but with three separate flights at the shortest possible intervals. This allows capturing the most prominent bands in the NIR and SWIR region and derive the two-band NRI (KOPPE et al. 2010) and four-band GnyLi (GNYP et al. 2014) vegetation indices simultaneously. Despite the higher number of camera modules, the weight of the existing system should not be exceeded and, if possible, significantly undercut. This should enable better integration of the complete multicamera system into a gimbal, and finally into various UAV models with sufficient payloads.

2 New concept of a multi-camera system

In 2020, a significant advancement in imaging sensor technology was marked by Sony's introduction of two VIS-SWIR-capable InGaAs sensors (TECHINSIGHTS 2021). These sensors, featuring resolutions of 0,3 and 1,3 Megapixels, were specifically designed for the industrial consumer market. However, the direct application of these sensors was not immediate because they required integration into usable image sensor modules by third-party industrial camera manufacturers. This integration was crucial for making the sensors suitable for practical image-processing applications.

In December 2021, this integration process was achieved with the availability of fully functional VIS-SWIR sensor modules from third-party manufacturers (e.g., ALLIED VISION 2021). Complementing this development was the introduction of sophisticated embedded control hardware capable of efficiently managing up to six image sensor modules. This hardware is fundamental in facilitating complex imaging tasks that require the synchronization and precise control of multiple sensors.

Recognizing the potential of these technological advancements, our research group has pursued the development of an improved VNIR multispectral multi-camera system. This completely redesigned system aims to utilize the improved form factor and spatial resolution of these VIS-SWIR sensor modules and integrate them into a coherent framework for advanced UAV-based imaging applications in the field of multispectral vegetation monitoring.

The result is a state-of-the-art 6-channel VNIR-SWIR multicamera system (Fig. 4) that exceeds the capabilities of its predecessor in terms of the number of channels. This new system leverages cutting-edge 2D InGaAs imaging sensors (400–1700 nm) and provides four times the spatial resolution of the former camera system. In a direct comparison of the flight parameters of both systems, the initial version reaches a calculated ground sampling distance (GSD) of 4.2 cm/px at a standard flight altitude of 35 meters AGL. In contrast, the new system, which maintained the same imaging parameters (focal length of 12.5 mm), achieved a significantly improved GSD of 1.4 cm/px. Additionally, by employing an 8 mm focal length in the new system, primarily for space and weight considerations, a GSD of 2.2 cm/px is achieved. In particular, this configuration maintained the same swath width as the predecessor, ensuring compatibility with the existing flight plans. Each of the six image sensor modules can be equipped with an individually selectable narrowband bandpass filter and corresponding prime lens, offering unparalleled spectral details and flexibility. The modern digital interface and its reduced weight improve its operability and integration with different UAV platforms, making it a versatile tool for a wide range of applications.

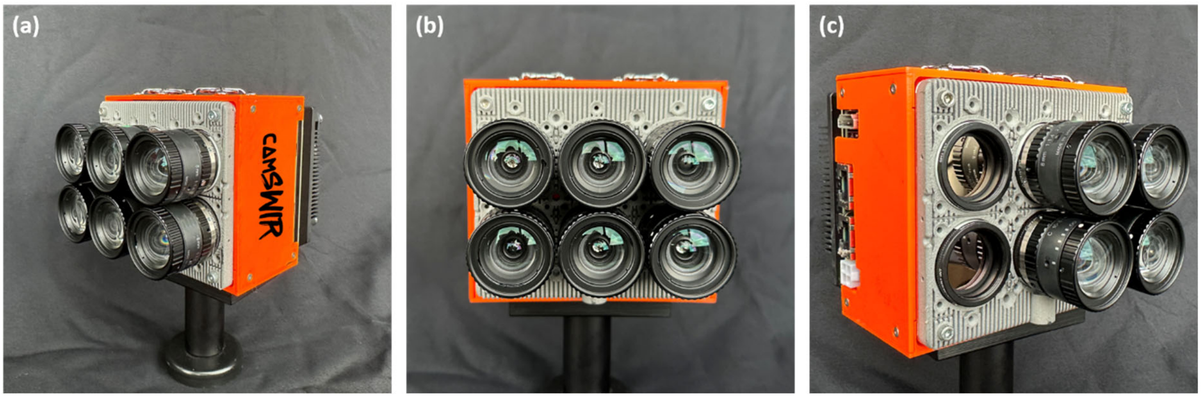

Fig. 4: Overview of the 6-channel VNIR-SWIR multicamera system. **(a)** Side view of the complete system. **(b)** Front view of the lens rig. **(c)** Side view of the lens rig with prime lenses of two channels removed for a clear view of the mounted narrow bandpass filters

Tab. 1 summarizes the most important properties of the two multi-camera systems for comparison. The most significant feature is the simultaneous acquisition of six bands, with higher spatial resolution and improved VIS sensitivity down to 400 nm. Apart from the reduction in radiometric resolution from 14 to 12 bits, we do not expect any reduced analysis performance. This does not necessarily represent a reduction in performance, especially for daylight applications and the fact that additional parameters are crucial for high-quality image data. Comparative tests are necessary in this respect to be able to make a final assessment. Finally, the significant weight reduction may allow for a longer UAV flight time per battery charge.

Tab. 1: Comparison of the two multispectral multi-camera systems. Parameters marked with (*) refer to the overall system.

Parameter	Two-Band System	6-Band System
Sensor	SCD / -unknown-	Sony IMX990
Sensor material	InGaAs	InGaAs
Spectral Response	600 to 1700 nm	400 to 1700 nm
Resolution (H × V)	640 × 512	1296 × 1032
Resolution	0,3 MP	1,3 MP
Shutter type	Global	Global
Pixel size	15 µm × 15 µm	5 µm × 5 µm
Bit depth	14 Bit	12 Bit
Focal Length	12,5 mm	8 mm
Mass*	2,2 kg (Atacama Version)	1,6 kg

As the bare-board image sensor module for each channel is not encapsulated into a standard housing, the application of narrow bandpass filters could also be redesigned from scratch and now consists of easy-to-modify off-the-shelf optomechanical components. Similar to the previous system, an individual insert must be manufactured or adapted for each filter. These parts must undergo some modifications for focal point correction, as the glass of the filter elements introduced into the image path shifts the focus behind the image plane and exceeds; therefore, the in-air 17.526 mm focus distance of the c-mount.

Furthermore, this newly developed camera system has also been designed as a blueprint for a starting point for other variants of the multi-camera system (Fig. 5). The modular system design now makes it possible to choose from a growing variety of image sensor modules that have the same form factor, but contain different sensor technologies and resolutions. Therefore, the InGaAs sensor modules can be replaced individually or completely by sensor modules in other wavelength ranges such as UV, VIS-NIR, or RGB with different sensor resolutions. Additionally, an individual prime lens and (narrow) bandpass filter can be applied to each channel, if necessary. Therefore, very specific application scenarios can be realized. The new form factor of the multicamera system is suitable for medium-sized UAVs with payloads of two to three kilos, including a versatile gimbal, as well as for manned aircraft such as gyrocopters, as mentioned in JENAL (2022).

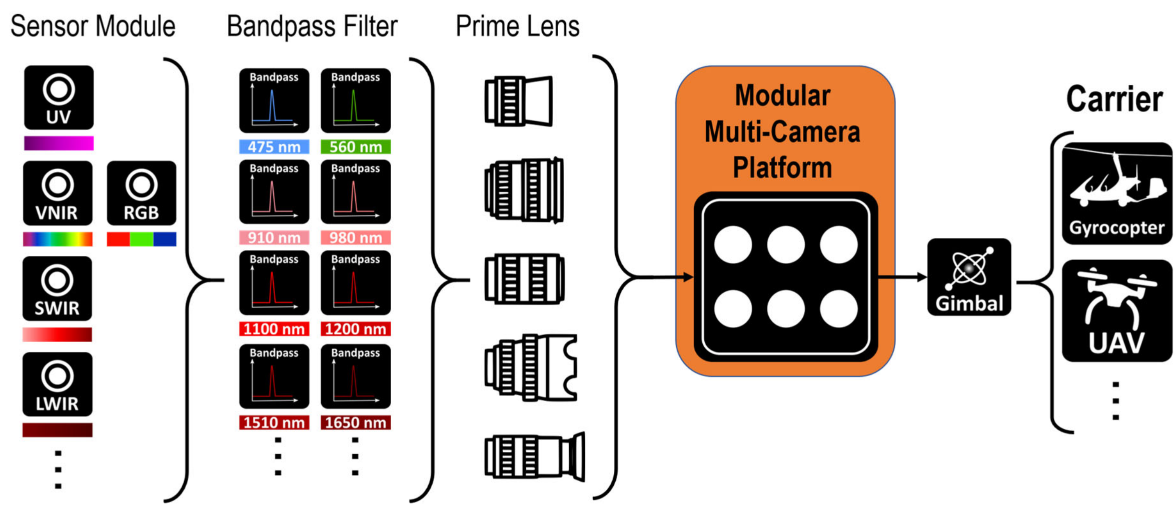

Fig. 5: Modular multi-camera platform concept

3 Conclusion & Outlook

As a successor to a UAV-based two-channel multispectral multi-camera system, we developed an enhanced 6-channel system, incorporating current technological advancements. Currently, this six-band system has achieved a Technology Readiness Level (TRL) in the range of 4 to 6. It is primarily used for UAV-based remote sensing in the short-wave infrared spectrum, featuring up to six channels, each with a resolution of 1,3 megapixels.

In the next phase of our project, we plan to conduct extensive laboratory tests that focus on comprehensively evaluating the performance of the system, including the temperature stability, optical quality, and spectral stability. This ensures its reliability and effectiveness before field deployment. Following these tests, the next crucial step is the integration of the system into a UAV, and extended validation will be performed in UAV-based applications for the upcoming growing season in 2024. This integration is crucial for exploring the potential of the system in aerial applications and for assessing its adaptability and operational efficiency in a dynamic environment. Therefore, several field campaigns are planned in agricultural experimental fields, accompanied by intensive spectral and destructive ground-truth data sampling.

Furthermore, our objective is to conduct a thorough comparison with the old system. This comparative analysis will be instrumental in demonstrating the technological advances and enhancements offered by our new system. By rigorously evaluating both systems across multiple parameters, we aim to provide a clear and quantifiable demonstration of the progress and improvements made, thus justifying the transition to the new system and setting the stage for further development.

This new development paves the way for more sophisticated and simplified UAV-based remote sensing solutions to more thoroughly investigate the SWIR domain of vegetation.

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