Preliminary verification of hyperspectral LiDAR covering VIS-NIR-SWIR used for objects classification

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ABSTRACT

Hyperspectral LiDAR (HSL) has been utilised as an efficacious technique in objects classification and recognition based on its synchronously obtaining spectral and spatial information. However, the spectral information obtained by most of the developed HSL was in the visible and near-infrared range (VNIR, 400–1000 nm). Whereas spectral information in a longer wavelength range showed more useful for classification and detection, such as detecting vegetation water content. This paper proposed and tested an eight-channel HSL prototype covering visible to near-infrared and even short-wavelength infrared (VIS-NIR-SWIR, 450–1460 nm) based on a Super-continuum (SC) laser. System calibration, range precision and spectral profiles experiments were carried out to test the HSL prototype. The spectral profiles collected by the HSL are consistent with those acquired by the commercial spectrometer (SVC® HR-1024). And these spectral profiles of plants, textiles, camouflage objects, and ore samples collected by the HSL, especially those in the SWIR range, can effectively reveal the health status of the plants, and classify the manufacturing materials and ore species. The unique characteristics of spectral profiles covering VIS-NIR-SWIR promote the HSL shows the potential applications on objects classification related to vegetation, mining and surveillance.

Introduction

Over the past few decades, both spectral imaging and light detection and ranging (LiDAR) have been used in a wide range of remote sensing applications. The spectral imaging system is beneficial for obtaining broadband wavelength spectral information. However, the traditional passive spectral information collecting is sensitive to shading and diffuse lighting effects and cannot provide direct spatial information of targets. Contrary to this, LiDAR provides an accurate object structure in three dimensions (3-D) through time-of-flight (TOF) measurement, which is critical in bathymetry, coastal mapping, vegetation detection and classification of the road (Inzerillo et al., 2018; Purkis & Brock, 2013). Multi-Spectral LiDAR (MSL), as a combination of LiDAR and spectrometers, can synchronously obtain spatial and spectral information. Titan MSL system (a typical airborne MSL) incorporates three monochrome laser beams (532 nm, 1064 nm, and 1550 nm) to perform the spatial information related to the wavelength used for land cover/target classification, coastal mapping and bathymetry (Budei et al., 2018; Fernandez-Diaz et al., 2016; Huo et al., 2018; Matikainen et al., 2017). These independent monochrome laser sources assembled in the MSL system need separate sensors with different response spectral ranges, further limiting the channel number of the system and increasing the difficulty of data processing. More spectral channels and a continuous coverage band LiDAR will show more effectiveness on vegetation detection and targets classification, for example, the vegetation water content (VWC) detecting and targets with similar colour distinguishing (Budei et al., 2018; Daoyi et al., 2005). However, based on the MSL structures, more spectral channels configuration needs amounts of laser sources and sensors. Whereas, SC laser based on photonic crystal fibre, which output the ultra-broadband laser comprising a continuum spectrum from VIS to SWIR (400–2600 nm), could provide the continuous coverage band for LiDAR (Dudley et al., 2006). Theoretically, the SC laser could provide tens or even hundreds of continuous spectral channels. Therefore, the systems based on SC laser, which can produce a continuous output in an ultra-broadband range, also has been defined as HSL system (Kaasalainen et al., 2007).
Based on the concept of HSL, many HSL prototypes with different waveforms and experiments have been initially developed and carried out by the Finnish Geospatial Research Institute (FGI) since 2007 for forestry remote sensing and classification (Chen et al., 2010; Hakala et al., 2012; Junttila et al., 2015; Kaasalainen et al., 2007; Puttonen et al., 2015; Suomalainen et al., 2011). A two-channel (600 nm and 800 nm) HSL has been proposed to distinguish the Normalised Difference Vegetation Index (NDVI) parameters of a coniferous tree (Chen et al., 2010) by FGI. After that FGI designed and implement a full waveform eight channels HSL system to produce spectral imaging and 3-D point clouds, and then used to test the 3-D distribution of chlorophyll or water concentration in vegetation (Hakala et al., 2012). A Tuneable HSL system with 10 nm spectral resolution in the spectral coverage of 500–1000 nm has been used to classify the plants’ leaves (Chen et al., 2010, 2019). The 3-D distribution of the backscattered reflectance and different vegetation indices, including NDVI (Junttila et al., 2015; Tucker, 1979), water concentration index (Hakala et al., 2012; Peñuelas et al., 1993), and Modified Chlorophyll Absorption Ratio Index (MCARI; Hakala et al., 2012; Zhao et al., 2016), also can be obtained from the data acquired by the HSL system. Further research and experiments in remote sensing and many other fields with HSL system were also carried out, such as artificial target detection in an outdoor setting, canopy-scale detection, indoor simultaneous localisation and mapping (SLAM), determination of aquatic systems, and so on (Haboudane et al., 2004; Jiang et al., 2020; Junttila et al., 2015; Kaiyi et al., 2020; Puttonen et al., 2015; Zhao et al., 2016). Other scientists in Britain (Wallace et al., 2012; Woodhouse et al., 2011), China (Jia Sun et al., 2017; Lin, Gong et al., 2016; Lin, Shi et al., 2016; Wang et al., 2014) and the United States (Xiaoli Sun et al., 2017) promote HSLs with different system configurations (Kaiyi et al., 2019; Shao et al., 2020) and applications in various fields. Although the SC laser used in this HSL system covers the wavelength range of 450–2400 nm, the spectral ranges of most of the HSL prototypes mentioned above cover only the VIS and NIR bands (450–1000 nm). However, the unique spectrum information of many objects is in the longer wavelength range. For example, the NDVI indices of the vegetation water content (VWC) is based on the infrared range of 1240–3000 nm, and the solar spectrum reflectance associated with liquid water is in the wavelength range of 1000–2500 nm (Daoyi et al., 2005; Holzman et al., 2021). Therefore, based on the HSL covering the VIS and SWIR bands, we extended the spectral band to SWIR and obtained some satisfying results, such as plant leaf classification.

In this paper, an eight-channel (540 nm, 670 nm, 800 nm, 990 nm, 1064 nm, 1100 nm, 1225 nm and 1460 nm) HSL prototype covering the VIS-NIR-SWIR band is proposed, designed and tested systematically. The spectral range (450–1650 nm) is doubled in most previous HSL systems, and HSL covers a wider spectrum that has not been extensively reported yet. A series of experiments using the proposed HSL are carried out in a laboratory environment, and the ranging and spectral information is collected to evaluate the system’s performance and investigate its potential applications. Firstly, we calibrate the system by comparing the echo intensity from different stranded reflector boards, and then examine its ranging performance and capability to discriminate similar “white” colour targets. Thirdly, four-stranded reflector boards and a spectrometer are used to examine its spectral collecting capability and calibrate the spectrum. Lastly, we collect the spectrum from three kinds of objects (plants, textiles and camouflage objects) to verify the HSL’s capability on classification and recognition of the target’s health status, colour, and materials, which could be widely applied in forestry inventory, agricultural monitoring, surveillance. A plagioclase ore sample’s spectrum is also measured to explore the HSL application filed in mining detecting and classification.

The following contexts are organised as follows: Section 2 presents the proposed HSL system and laboratory experiments, the experiment results are discussed and analysed in section 3, and conclusions are drawn in section 4.

System design

The schematic setup of the proposed eight channels HSL system is shown in Figure 1. An SC laser (Leukos © SCM 30-HE-450) spreading over a 450–2400 nm laser beam is used as the laser source. The SC laser’s pulse width (full width at half maximum, FWHM) is 1 nanosecond (ns) at a repetition rate of 25 kHz, and the average power is more than 170 mW. The SC laser beam is collimated with a fibre collimator and then through a reflected fibre collimator based on the parabolic mirror to mitigate its chromatic aberration. A pellicle beam splitter reflected 2% of the collimated laser beam to a photodetector, and the remaining 98% laser is transmitting. The photodetector that received the reflected laser beam outputs a trigger signal to a high-speed oscilloscope or an oscilloscope card. An off-axis parabolic mirror (76.2 mm diameter, 90° off-axis angle, 228.6 mm effective focal length) with a hole (10 mm diameter, parallel to the parabolic mirror’s optical centreline) is used as the primary collecting optic. The parabolic surface is coated with gold, making it with an average reflectivity of more than 90% in the 0.4–20 μm range to secure the system-ranging performance. The scanning mirror points the main beam to the target and reflects the target’s echoes to the parabolic mirror as well. A single photodetector can seldom cover a spectral range from VIS to SWIR.
band for high-speed pulse detection, even based on the latest photonics technology. Therefore, the reflected echoes are split into two channels by a long pass dichroic mirror (cut-off wavelength of 950 nm). The spectral beam splitter is installed in this HSL system’s aft optics between the parabolic mirror and spectrometric devices, and the reflection band is 420–900 nm (the average reflectivity $R_{\text{avg}} > 95\%$ and the absolute reflectivity $R_{\text{abs}} > 90\%$), the transmission band is 960–1600 nm ($T_{\text{avg}} > 90\%, T_{\text{abs}} > 85\%$). Two filter wheels equipped with optical filters are mounted before APD sensors and used as spectrometric devices to select the backscattered echo wavelength. The first filter wheel equipped with three optical filters (540 nm, 670 nm, and 800 nm) used for spectral selection for the reflection band (420–900 nm) and the other one equipped with five optical filters (990 nm, 1064 nm, 1100 nm, 1225 nm, and 1460 nm) is utilised in the transmission band (960–1600 nm) optical path. The central wavelength ($\lambda$) and the bandwidth ($\Delta\lambda$) of the VIS and NIR (VNIR) and SWIR optical filters are listed in Table 1.

The VNIR echoes transmit the first group optical filters and focus on a Si-APD sensor (MentoSystems® APD210, 400–1100 nm). The SWIR echoes transmit the other group optical filters and focus on an InGaAs-APD sensor (MentoSystems® APD310, 850–1650 nm). With such a system schematic, the selected bands’ combinations can be arbitrarily configured to optimise specific research. Both of the two APD sensors have built-in amplifiers. However, the InGaAs-APD sensor’s gain is one order of magnitude lower than that of the Si-APD sensor. The maximum gain of the two APD sensors is shown in Table 2. Thus, an extra high-speed amplifier is adapted to compensate for the lower gain of the InGaAs-APD sensor, making the received signals in the SWIR-band more evident and legible.

**Figure 1.** Schematic setup of the eight-channel HSL.

**Table 1.** The central wavelength and bandwidth of the filters.

|        | VNIR       | SWIR       |
|--------|------------|------------|
| $\lambda$ | 540 nm | 670 nm | 800 nm | 990 nm | 1064 nm | 1100 nm | 1225 nm | 1460 nm |
| $\Delta\lambda$ | 20 nm | 20 nm | 20 nm | 15 nm | 15 nm | 15 nm | 11 nm | 10 nm |
In this HSL system, a high-speed digitiser card (Spectrum-M4x), with a sampling rate of 5 GS/s, is used to record the output analogue signals of the two APD sensors, and the 200 picoseconds (ps) sampling interval and equals 3 cm ranging resolution. Different sampling signals, such as trigger signal, VNIR signal and SWIR signal, are detected and recorded synchronously by the digitiser card, which also recording procedure when the different optical filter pairs in VNIR and SWIR are selected by turning the filter wheels.

### Experiment and materials

Based on the system designing, we measure the HSL prototype’s performance through system calibrated experiment, range precision experiment, and spectral profiles experiment; more details are shown in Table 3.

System calibration experiments employ reflective boards with different reflections to test its performance on signal collecting for each channel, and different distances calibration were also carried out. The range precision experiment employs a ceramic cup and a reflective board to preliminarily test its range precision accuracy and performance on targets classification. The spectral profiles experiment employs several kinds of targets with different characteristics to test its spectral profiles accuracy and performance on targets classification. A commercial spectrometer (SVC® HR-1024) is employed during the spectral profiles experiment to collect the echoes signal as a reference. The reference data are also used to calibrate these data collected by the HSL prototype. All the experiments are carried out in a low-light environment to obtain a high signal-to-noise ratio (SNR) result for more precise-ranging measurements and better spectral information.

Reflective boards used in these experiments are 99% reflection from SVC®, and 5%, 20%, 40%, 60%, 70% from a local manufacturer. The reflective boards with 99% reflection combined with a white ceramic cup are used to verify the HSL’s performance on the ranging capability, and the 99% reflective board is also used for system calibration and spectral profiles experiments as a reference. The target set in these experiments is shown in Table 4. In the spectral profiles experiment, the target set intends to test its application in different fields, and Figure 2 shows these targets. The water concentration in plants can be obtained from the spectral profiles of the three plants (Scindapsus with different statutes) and then used to distinguish different plants, which are widely used in precision agriculture applications. Distinguishing colour capability, as an important performance of the HSL system, were verified by testing three textiles with a different colour in appearance (white, black, brown) and made of different materials (cotton and nylon). Furthermore, the spectral profiles of zinc alloy Hummer model and camouflage net, which exhibit similar colour in appearance but are composed of different materials, were used to test the potential capability of the HSL on camouflage recognition. In addition, the anorthite, one of typical plagioclases in the moon, was tested to verify the HSL’s classification capability on mining. All the targets were placed at 5 m from the HSL system during the spectral profiles experiment.

### Data processing

During all the experiments, we collect eight series of data for each wavelength of any single target in a different area and give an averaging value to get a more typical result. All the data in the range precision and spectral profiles experiments are calibrated by the 99% reflective board. Additionally, the echo waveform was processed with Gaussian fitting. The area of the Gaussian function is considered to be the echo intensity at that spectral channel. Therefore, through testing the ratio of echo intensity at each channel from different targets and then compared with the reference board’s data, we can obtain the reflectance spectrum of each target more accurately. The reflectance spectrum calculation is presented in Equation (1). The reference data were collected by the SVC spectrometer, which is the radiance spectra curves of the targets. Therefore, the reflectance spectral curve can be calculated directly according to each target’s radiance spectrum ratio to the reflective board. The calculation is shown in Equation (2).

| Sensor type | Si-APD | InGaAs-APD |
|-------------|--------|------------|
| Spectral range | 400–1000 nm | 850–1650 nm |
| Maximum gain | $2.5 \times 10^7$ V/W @800 nm | $2.5 \times 10^6$ V/W @1500 nm |
| Maximum photosensitivity | 50 A/W @800 nm | 0.8 A/W @1500 nm |

### Table 3. Experiment setting and proposal.

| Experiment | Test propose |
|------------|--------------|
| ① System Calibration | Signal collecting for each channel; Signal collecting at different distances. |
| ② Range Precision | Testing accuracy of ranging; Classification. |
| ③ Spectral Profiles | Distinguish and classification targets; Monitoring the plants; Distinguish targets’ colour and materials; Camouflage recognition; Analysis of ore’s species. |
Table 4. Target setting in experiments.

| Category        | Targets                              | Experiment | Effect in experiment                        |
|-----------------|--------------------------------------|------------|---------------------------------------------|
| Reflective Boards | 99%                                  | ①②③       | Calibrated system and spectrum               |
|                 | 70%                                  | ③          | Ranging accuracy; Targets classification     |
|                 | 60%                                  | ①②         | Calibrated spectrum                          |
|                 | 40%                                  | ③          | Calibrated system and spectrum               |
|                 | 20%                                  | ③          | Calibrated spectrum                          |
|                 | 5%                                   | ①②③       | Calibrated system and spectrum               |
| Ceramics        | White cup                            | ③          | Ranging accuracy; Targets classification     |
| Plants (Scindapsus) | Health                              |            | Spectral analysis and distinguish            |
| Models          | Hummer Model                         |            | Spectral analysis; Materials distinguish     |
| Textiles        | Camouflage net                       | ③          | Spectral analysis;                           |
|                 | White cotton cloth                   |            | Colour and materials distinguish;           |
|                 | Black cotton cloth                   | ③          |                                             |
|                 | Brown nylon cloth                    | ③          |                                             |
| Plagioclase     | Anorthite                            | ③          | Spectral analysis                            |

Figure 2. Targets used in the spectral profiles experiment, three plants (grow in water, health, dry and withered Scindapsus), three cloth (white and black cotton cloth, brown nylon) and two toy models (zinc alloy model and camouflage net).
\[
\text{Re}_{\text{target}}(\lambda) = \frac{A_{\text{Gaussian,target}}(\lambda)}{A_{\text{Gaussian,whiteboard}}(\lambda)} \\
\text{Re}_{\text{target}}(\lambda) = \frac{R_{\text{radiance,target}}(\lambda)}{R_{\text{radiance,whiteboard}}(\lambda)}
\]

Where \(\text{Re}_{\text{target}}(\lambda)\) refers to the reflectance of each target; \(A_{\text{Gaussian,target}}(\lambda)\) and \(A_{\text{Gaussian,whiteboard}}(\lambda)\) are the areas of the Gaussian function of the target and whiteboard respectively; the \(R_{\text{radiance,target}}(\lambda)\) and \(R_{\text{radiance,whiteboard}}(\lambda)\) are the radiance spectra of each target and the whiteboard.

**Results and discussion**

**System calibration**

The precision of the intensity calibration of the HSL system is essential to reveal the physical essence of spectral collecting. Therefore, three reflective boards (99%, 60%, 5%) were placed at 9 m in front of the laser source to calibrate its signal collecting for each channel. The echo waveforms for each channel increased as the reflection of the reflective board from 5% to 99%, shown as in Figure 3 (a). Furthermore, the echoes from the 99% reflective board placed at distances of 4.5 m, 6 m, 7.5 m, and 9 m are also used to calibrate the HSL system, and the results are shown in Figure 3 (b). The echoes intensity for each channel decreases as the distances increase from 4.5 m to 9 m. Such phenomenon fit well with the LiDAR Equation: (Chen et al., 2019)

\[
P_e = \frac{P_l D_i^2}{4 \pi R^2 \beta_l^2} \sigma
\]

where \(P_e\) is the echo power received, \(P_l\) is the laser source power, \(D_i\) is the aperture diameter of the receiver optics, \(R\) is the distance, \(\beta_l\) is the laser beam width, and \(\sigma\) is the backscatter cross-section as follows.

**Range precision**

Figure 4 shows the waveforms (@1100 nm) of the white ceramic cup and a 99% reflective board (labelled as "whiteboard") collected by the high-speed oscilloscope in the HSL system. The white ceramic cup and reflective board are placed at 4.7 m and 6.1 m from the laser source. The black curve in Figure 4 indicates that the peak position of the trigger signal waveform is also utilised as the start point of the time-of-flight measurement. The red curve indicates the echo waveform from the ceramic cup, and the blue curve indicates that from the whiteboard. The positions of the three peaks at 35 (black), 192 (red), and 239 (blue) are stable, which implies that the distances of the ceramic cup and whiteboard from the laser source are 4.71 m and 6.12 m, respectively. Furthermore, the different echo amplitude of the red and blue peaks imply that the two targets with the same colour in appearance, are should be different targets with different reflectance. However, the difference of amplitude between the two peaks is not so obvious in the VNIR channels. Under current optical system settings, all the experimental

![Figure 3](image_url)

*Figure 3.* The echo waveforms of (a) the reflective boards (99%, 60%, 5%) at a distance of 9 m, and (b) the reflective boards of 99% at distances of 4.5 m, 6 m, 7.5 m, and 9 m.
data are processed by the method illustrated in the section of data processing to increase the accuracy of the ranging. In addition, the reference data collected by a spectrometer shows that the ceramic cup’s reflection is 83.8% at 1100 nm, which is much lower than the reflective board (99%).

**Spectral profiles**

With the proposed HSL prototype, the initial echo waveforms of eight channels from a zinc alloy camouflage model (Hummer model) and three plants (health, dry and withered, grow in water *Scindapsus*) are measured, and results are shown as in Figure 5. In Figure 5, we can observe that the four targets’ spectrum exhibit similar variation tendencies in the VNIR range, but there are significant differences in the SWIR range, especially for the longer wavelength band channels (1460 nm). The health *Scindapsus* and the *Scindapsus* grow in water with a similar spectrum variation tendency in the SWIR band. However, both are different from the ones with dry and withered leaves. Although the Hummer model’s SWIR spectrum variation tendency is similar to the *Scindapsus* with dry and withered leaves, the value is vastly different. We also can easily distinguish the Hummer model and the three plants in different grow statues through the SWIR channels (especially for the channel at 1460 nm). However, some of the recovered spectral curves are still misdescribed to the targets’ spectral characteristics. Several factors are causing the incorrect description:

1. The SC laser source’s spectral power density is un-flattened. The maximum SC laser’s power density peak (1064 nm) is three orders of magnitude higher than the minimum (400 nm).
(2) The gains of the two APD sensors are different. The maximum gain of the InGaAs-APD sensor (for the SWIR bands) is lower than that of the Si-APD sensor (for the VNIR bands) by about one order of magnitude, shown in Table 2. And the InGaAs-APD sensor is significantly less sensitive than that of the Si-APD sensor. Therefore, a high-speed amplifier with 36 dB gain was employed to further amplify the SWIR echoes’ signals.

(3) The bandwidth of the filters is largely different, as shown in Table 1. These VNIR filters with a wider Δλ allow more energy to pass through than these SWIR filters. Moreover, the bandwidth of the several SWIR filters is also different.

The initial echo waveforms of each spectral channel, from reflective boards with reflectivity of 5%, 20%, 40%, and 70%, are collected by the promoted HSL and a commercial spectrometer. The results are used to test the HSL’s capability of spectral information collecting. And all the results are also processed with Gaussian fitting and calibrated with the 99% reflective board. The spectral of all the four reflective boards measured by the HSL and the spectrometer are coincide well, shown as in Figure 6. And the amplitude of the HSL measurement is proportional to the nominal value of each reflective board. The results confirm that the HSL system fits the targets’ spectral measurements over the waveband from VNIR to SWIR.

Using the spectrum of the reflective board collected by the HSL and the spectrometer, we calibrate the spectrum of the three plants over the wavelength of VIS-SWIR. Figure 7 presents the calibrated reflectance of the three Scindapsus (shown in Figure 2) in different health statuses based on their lack of water. The two healthy Scindapsus (label as “health” and “grow in water”) exhibit similar spectral profiles in the VIS range (540 nm and 670 nm), and the Scindapsus grow in water exhibits a higher reflectance at 800 nm and a lower reflectance at 1064 nm, 1100 nm and 1125 nm. The reflectance at 1460 nm, which implies the water content in the healthy Scindapsus, is almost the same. Differently, the dry and withered Scindapsus presents a different spectral profile with higher reflectance (0.6) from NIR (800 nm, 1064 nm and 1100 nm) band, especially for the SWIR spectrum at the 1460 nm, which is much higher than that of the other two healthy Scindapsus. The obvious difference of the spectrum, especially for the SWIR range (1225 nm and 1460 nm), among the three Scindapsus, exhibit an optional application of the HSL on monitoring and recognising the plants’ health status, which is very useful in precision agriculture.

The spectrum of the Hummer model and camouflage net, which exhibit green colour different from the plants, are measurements to verify the HSL’s capability to distinguish colour in appearance and materials,

![Figure 6](image_url). The spectral reflectance (blue) of the reflective boards with reflection of (a) 5%, (b) 20%, (c) 40%, (d) 70% collected by the HSL and the reference(black) collected by the spectrometer.
Thus, the spectral reference of the three plants can be classified in VIS and SWIR bands. Although the Hummer model’s colour is similar to the Scindapsus and the camouflage nets (as Figure 2 presents), the Hummer model presents a flat spectral profile from VIS to SWIR band, and the camouflage net shows a largely different spectral profile in both the VIS and SWIR bands. Although the spectrum of the camouflage net is similar to the two green plants in the VIS band (Figure 8), it exhibits large differences in the NIR and SWIR spectrum. Thus, utilising these unique characteristics in the SWIR band, we can classify objects that exhibit similar spectral reflection in the VIS band (the same colour and appearance) but different in the NIR and SWIR bands. It is very important for the HSL used in camouflage recognition, material identification and many other fields.

The spectral comparison results of three cloth with different colours are shown in Figure 9. The results are also processed with Gaussian function and calibrated. We can perceive that the reflectance wave spectrum of the three cloth collected by the HSL is nearly equal to the reference spectrum from the spectrometer. However, there are still some unmatched channels, such as the black cloth at the channel of 670 nm and the brown cloth at 1225 nm. Although the three cloth objects are all planar objects, there are still some uneven planes compared with the standard reflective board. The reflects factors include: 1) folding, to prevent the potential risk that might disturb the spectral measurement, all cloth material has been folded at least twice to prevent the spectral leakage of the support frame; 2) texture, especially for the brown cloth, it is canvas-type cloth. Besides, compared with the spectrum of these standard reflective boards, the variance of the spectral results of the black/white/brown cloth is more obvious. The difference of the VNIR band channels caused by the different colours (in appearance) and that of the SWIR spectral should be related to its materials: the black and white cloth are all made of cotton, and the brown one is nylon cloth. Another interesting phenomenon is that the black cloth is only “black” in the VIS band. Compared with the spectral profile of the 5% standard reflective board previously discussed, the reflectance of the black cloth is considerably higher in NIR and SWIR bands.

Above all, we can observe that the HSL measured results coincide well with the spectrometer in all green objects. However, the variances between the HSL and the spectrometer measurements are also noticeable,
especially for the green camouflage net, healthy *Scindapsus*, dry *Scindapsus*, and the one grown in water. The explanations for the variance are:

(1) For these flat objects, such as the cloth and reflective boards, the variation is minor, and a similar phenomenon also can be observed in the previous comparison.

(2) For the camouflage net and plants, the laser points on the targets might be slightly different during the test, and all the objects are measured by the HSL firstly and then by the spectrometer.

(3) The incidence angle might also vary during the test if the plants’ surface cannot be treated as a lambert object and the luminous intensity changes during the two measurements.

Additionally, the HSL can also be used for geological material detection and classification. We preliminarily utilise the HSL to explore the possibility of tunnel modelling or mineral disaster prevention applications with the Unmanned Ground Vehicle (UGV) platform (Chen et al., 2016). The spectral reflectance of anorthite, one typical plagioclase sample, is measured using the proposed HSL, and the results are shown in Figure 10. We can perceive that the HSL measurement of the plagioclase coincides nicely with that collected by the spectrometer. And we also have reported the spectral characterises of coal/rock collected by HSL in VIS and NIR channels in reference (Shao et al., 2019). Besides as one of the geological materials, anorthite is also a significant component of the moon and asteroids. Thus, this HSL cover the longer wavelength bands can also be used as a potential method for deep space exploration science, aside from its geological application. With a single HSL instrument, a 3-D model with surface material information can be generated. It might be financially beneficial for deep space research. Therefore, we can predict that the HSL sensor can be utilised for 3-D model navigation and the material classification with extended spectral range, especially for the HSL with the spectrum extending to the SWIR range (Shao et al., 2019). And many other geological materials spectrum will collect by the proposed HSL.
system to explore its application in space remoting sensing and deep space research. Furthermore, the SWIR range information may contain more details about the element and the geological material structure.

Conclusions

In this paper, an eight-channel HSL system covering VNIR- SWIR bands with full waveform capability is proposed, developed and tested. In this HSL system, we successfully extend the HSL’s waveband from VNIR to SWIR. It doubles the effective spectral range by 1) dividing the echoes into two optical paths (VNIR section and SWIR section) using a long-pass dichroic mirror as the beam splitter, and 2) adopting devices such as optical filters wheels, InGaAs APD sensors and amplifier, to receive and detect the SWIR echoes. System calibration with standard reflective boards verified the system’s performance, and the range precision evaluation exhibited its excellent-ranging performance. Judged from the referenced spectra collected by a spectrometer, the spectral profiles collected by the of the reflective boards, plants, camouflage objects, textiles and plagioclase measurement exhibit its perfect performance on spectral profiles. The spectral profiles of Scindapsus under different growing conditions, cloth, Hummer models and camouflage net confirm that the HSL cover VIS-NIR-SWIR is effective in obtaining spectral characteristics and classifying the targets. The wider wavebands, especially those in the SWIR range, further promoted by the HSL, exhibit substantial potential application in remote sensing fields, such as forestry investigation, autonomous driving, target recognition and distinguishing, and safety-related surveillance. This work paves the road for the advanced HSL system with more channels operated in wider wavebands and further applications in classification and recognition.

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Disclosure statement

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