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Binary pressure-sensitive paint measurements using miniaturised, colour, machine vision cameras

Mark Kenneth Quinn¹

¹ Lecturer in Aerospace, School of Mechanical Aerospace and Civil Engineering, the University of Manchester, United Kingdom

E-mail: mark.quinn@manchester.ac.uk

1 ABSTRACT

Recent advances in machine vision technology and capability have led to machine vision cameras becoming applicable for scientific imaging. This study aims to demonstrate the applicability of machine vision colour cameras for the measurement of dual-component pressure-sensitive paint (PSP). The presence of a second luminophore component in the PSP mixture significantly reduces its inherent temperature sensitivity, increasing its applicability at low speeds. All of the devices tested are smaller than the cooled CCD cameras traditionally used and most are of significantly lower cost, thereby increasing the accessibility of such technology and techniques. Comparisons between three machine vision cameras, a three CCD camera, and a commercially available specialist PSP camera are made on a range of parameters and a detailed PSP calibration is conducted in a static calibration chamber. The findings demonstrate that colour machine vision cameras can be used for quantitative, dual-component, pressure measurements. These results give rise to the possibility of performing on-board dual-component PSP measurements in wind tunnels or on real flight/road vehicles.

Keywords: Pressure-Sensitive Paint, Binary PSP, Machine Vision

2 INTRODUCTION

Pressure-sensitive paint is a measurement technique increasingly found in many laboratories around the world as it offers the ability to measure pressure quantitatively around an entire (and often complex-shaped) model. This ability has led to a rapid increase in the number of PSP-based research articles being published in recent years as researchers have found even more applications for the technique. These include steady flows, unsteady flows, transient flows, high- and low-speed flows and, rotating flows; however, one issue that has always dogged the technique and prevented its use in certain wind tunnel experiments: its inherent temperature sensitivity [1], [2]. To this end, researchers have endeavoured to compensate for the effect of temperature on PSP by measuring the temperature on the surface using temperature-sensitive paint [3], [4], infrared cameras [5], or by using spot thermocouple measurements. However, the mixture of a second, pressure-insensitive, component has yielded promising results by reducing temperature sensitivity and has increased the possible measurement range of PSP. These paints, known as dual-component paints (or binary paints), emit light of different wavelengths in response to changes in pressure and temperature respectively, meaning that the signals can be separated and measured independently. The measurement of such

paints have often been performed using separate cameras with differing optical filters which, although successful, leads to the issue of image registration being required to process the data, as discussed by Le Sant & Mérienne [6]. Other measurement systems have used a single camera and a filter wheel to capture the two images separately [7], [8], although this increases acquisition time. The use of colour cameras to perform such measurements has been reported [9], [10], but without great detail in terms of camera selection and performance. This study aims to build on the work of Quinn et al. [11] and demonstrate the use of single, small-scale, machine vision colour cameras for such dual-component PSP measurements and also introduce a comparison with an industry-standard, commercially available camera and a novel camera that utilises three individual detectors and a prism.

2.1 PSP technique

Descriptions of the PSP in literature are numerous, so only a brief overview will be given here with special reference to binary PSP (readers are encouraged to investigate the review paper by Gregory et al. [12] and the comprehensive book by Liu and Sullivan [2] for more details).

PSP is a technique based on the oxygen quenching of luminescence that allows field measurements of pressure on a surface. The active molecule of PSP is known as a luminophore. The luminophore is dissolved in an oxygen-permeable binder material with solvents and other additives and sprayed onto a suitably prepared substrate. PSP absorbs light of a specific wavelength (usually around 390 nm) and is excited to a higher electronic state. The excited luminophore molecule then gives this energy away, either by emitting a longer wavelength of light (usually around >600 nm) or via contact with a deactivating/quenching molecule (often oxygen). By measuring the differential amount of light emitted, we can measure the amount of oxygen present and, in turn, the pressure. A typical spectral plot for a single-luminophore PSP is given in Figure 1 (a). The typical measurement system for PSP incorporates a narrowband excitation source or a broadband excitation source with appropriate filters and an imaging device with appropriate filters (Figure 1 (b)). The filters are used to separate out the input and output signals.

(a)

(b)

Figure 1. a) Absorption spectra and emission spectra of a PSP containing PtTFPP and b) basic set-up of a PSP system [13]

The basic PSP system is known as a radiometric system. This system measures the intensity of light emitted by the paint and relates it to a reference condition. The relationship between this reference condition (sometimes called a wind-off condition) and the test condition is expressed using a modified version of the Stern-Volmer equation given below:

$$\frac{I_{ref}}{I} = A(T) + B(T) \frac{P}{P_{ref}} \quad 1$$

where I is the pixel intensity, P is the pressure, A and B are coefficients which are functions of temperature (T), and the subscript ref denotes a reference condition. This equation is applied pixel-wise to the PSP data and, given a suitable calibration, allows for calculation of the pressure at every pixel.

Binary PSP has two components which respond differently to changes in pressure and temperature. Ideally, these components are excited with the same wavelength of light but emit at different (and therefore separable) wavelengths; in other words, they have a different Stokes shift.

Figure 2. Spectral output of ISSI Binary PSP at a) constant 293 K with variable pressure and b) constant 10 kPa pressure and variable temperature

Figure 2 a) shows the spectral output of the ISSI BinaryFIB paint [14] as measured by the Thorlabs spectrometer as detailed in section 3.1. In this figure the paint is exposed to a range of pressures from 10 kPa to 150 kPa at a constant temperature. The figure shows the clear response of the red part of the spectrum with minimal response in the green portion. Figure 2 b) shows the response of the binary PSP when it is exposed to 10 kPa pressure and a range of different temperatures from 273 K to 313 K. The response of both green and red portions of the spectrum to temperature is visible. By taking what is known as the *ratio of ratios* of the green and red portions on the spectrum (equation 2), the temperature effect on the pressure results can be significantly reduced.

$$\frac{\frac{I_{refRED}}{I_{RED}}}{\frac{I_{refGREEN}}{I_{GREEN}}} = A(T) + B(T) \frac{P}{P_{ref}} \quad 2$$

There are several different methods of separating out different wavelengths within a camera to give a colour image. The most common technique is using a Bayer filter which is a set of filters which are applied in a coded fashion across four pixels in a square with the pattern repeating across the whole sensor. Other methods involve the use of multiple detectors and prisms to separate out the colours in what is known as a *triple-chip* camera or, alternatively, using a sensor which is based on the penetration depth of each wavelength of light, known as a Foveon sensor. In this study, Bayer-based cameras and a three CCD camera will be used.

2.2 Imaging characteristics

The EMVA 1288 standard [15] describes and details the many different metrics for image and camera performance evaluation. Quinn et al. [11] estimated relevant parameters for PSP acquisition of monochrome PSP data (temporal stability, linearity, signal-to-noise ratio).

Measurements taken with the Basler Ace 2040-90uc, Teledyne Genie Nano C1920 and the Ximea XiMu9PM were similar to their monochrome counterparts as measured in the previous study; however, their performance is included here for completeness. An additional characteristic of the cameras used in this study is the performance of the Bayer filter for colour separation. This performance will be discussed by estimating the colour cross-talk between the green and red channels by using digitised versions of the quantum efficiency (QE) curves from the camera datasheets.

Measurements of the temporal stability, linearity and signal-to-noise ratio and colour cross-talk will be discussed for all cameras.

2.2.1 Temporal stability

As machine vision cameras do not have active cooling, they may heat up during subsequent exposures and change the values present in the image. This heating can be caused by the operating environment or due to self-heating from internal electric currents. As the sensor or camera body heats up, there may be spatial changes across the sensor which could be significant for PSP imaging and therefore need to be quantified.

2.2.2 Linearity

The response of a camera to incoming photons should, ideally, be linear in that twice the number of photons per given area should result in twice the signal output. This is broadly true over the majority of the dynamic range of a camera; however, at the edges of the dynamic range this assumption tends to break down and the response becomes non-linear. The output from the camera at different exposure times can be plotted and, using a least-squares regression, have a linear curve fitted to it. The maximum deviations from this curve are used to estimate the non-linearity of the camera response as a single parameter:

$$NL = \frac{|\delta I_{+ve}| + |\delta I_{-ve}|}{I_{max}} \times 100, \quad (1)$$

where NL is the non-linearity in percent, δI_{+ve} is the maximum positive deviation from the least-squares curve, δI_{-ve} is the maximum negative deviation from the least-squares curve and I_{max} is the maximum signal (12 bit = 4096). It is important that sensors used for quantitative imaging have a good linearity, otherwise a more complicated lookup-table approach must be used.

2.2.3 Signal-to-noise ratio

This is an extremely important parameter for imaging, as it demonstrates how much of a reading can be attributed to noise and how much can be apportioned to the measured quantity. Signal-to-noise ratio (SNR) is often quoted in decibels:

$$SNR = 20 \times \log_{10} \frac{\mu - \mu_{dark}}{\sigma}, \quad (2)$$

where μ is the pixel exposure, μ_{dark} is the dark level for this given exposure and σ is the standard deviation of the pixel exposure levels. The SNR can be improved by averaging multiple images, something which is often done in PSP tests and is investigated in this study.

2.2.4 Colour cross-talk

Bayer filters are usually absorption-based bandpass filters that pass a range of wavelengths that correspond to the three colours of red, green and blue. However, these filters are not perfect in that the red channel will contain some wavelengths from the blue and green part of the spectrum, as

shown in Figure 3. The Bayer filter-based cameras show significant spectral overlap between the three colour channels. However, the three-CCD prism-based camera in Figure 3 b) shows significantly less overlap, and what overlap there is could be removed by a notch filter. The subsequent camera plots in this figure show that the ISSI PSP CCD has a relatively low level of colour cross-talk, the lowest of the single-sensor cameras. The smaller machine vision cameras (particularly the Ximea XiMU Figure 3 e)) show significant cross-talk between the green and red channels.

Figure 3. Normalised colour response curves for a) Basler ACE acA2040-90uc, b) JAI AT200GE, c) ISSI PSP CCD, d) Teledyne Genie Nano C1920 and e) Ximea XiMU9PM

The impact of colour-cross talk is that a change in pressure could be represented as a change in temperature or vice-versa, meaning that the two-component PSP technique may not yield better results than single-component PSP measurements.

2.3 Imaging devices

The relevant specifications of the imaging devices used in this study are given in Table 1. Of note are the different Bayer codes which are required for colour processing.

Table 1. Comparison of imaging devices used

Camera Name	Size (mm)	Resolution (pixels)	ADC (bits)	Shutter Type	Colour Processing	Max Frame Rate (Hz)
Basler ACE acA2040-90uc (CMOS)	29 × 29 × 47	2048 × 2048	8, 12	Global/Progressive	Bayer (BGGR)	90
JAI AT200GE (Three CCD)	55 × 55 × 98	1624 × 1236	10	Progressive	Three CCD Prism	15
ISSI PSP CCD (CCD)	46 × 46 × 69	1600 × 1200	8, 10, 12	Global	Bayer (GRBG)	35, 44
Teledyne DALSA Genie Nano C1920 (CMOS)	44 × 29 × 41	1920 × 1200	8, 12	Global	Bayer (RGGB)	38
Ximea Sub-Miniature XiMU9PM (CMOS)	15 × 15 × 9	2594 × 1944	8, 12	Progressive	Bayer (GRBG)	5.8

The cameras used in this study range from a traditional camera size to extremely small machine vision cameras. Specifically, the XiMU camera is an order smaller than traditional cameras and opens up the possibility of field measurements being conducted in very tight spaces, such as intakes.

An interesting feature to note about the AT200GE camera is that as it has three separate CCD sensors on board, they can be controlled independently and have unique exposure times. This feature allows the user to maximise the signal-to-noise ratio in the measurements, as there is often a large mismatch in the signal levels between the red and green channels (as can be seen in Figure 2).

2.3.1 Software

Software to control the machine vision cameras was written in LabVIEW using the Vision Acquisition Toolbox, taking advantage of the GenICam standard where possible. This standard allows for the quick development of camera-control software that is easily portable from one camera to another [16]. Unfortunately, as the Ximea camera is USB 2.0, it is not able to communicate using the GenICam standard; however, Ximea have developed a LabVIEW SDK which allows for the creation of similar software to that used by the GenICam controlled cameras. All of the parameters that could be controlled on board the camera required investigation to ensure that no on-board processing of the images was enabled by default. This was achieved by using National Instruments Measurement & Automation Explorer (NIMAX) and then programmatically setting these parameters using property nodes within LabVIEW. The following parameters needed to be set for the machine vision cameras (note that the names of the parameters are exactly as they are in LabVIEW):

- BlackLevel = 0
  - The threshold below which the camera reports a zero level. This was set equal to zero, thereby maximising the measurement range available.
- PixelFormat = 12 bit (10 bit for AT200GE)
  - Default bit depth is 8 bit for all cameras, but was set to 12 bit for greater resolution where possible.
- ExposureAuto = off
  - Otherwise the camera will adjust the exposure time to “correct” the exposure.
- GainAuto = off
  - Otherwise the camera will try to automatically adjust the gain to “correct” the exposure.
- Gain = 1

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- So that this value is set and controlled.
- AcquisitionFrameRate = as required
  - Fixed for ISSI PSP CCD at 35 Hz
- ExposureTime = as required
  - Three exposure times were required for the AT200GE as its three CCDs can be controlled independently.

Once all of these parameters were set and the camera reported that it was ready, data was captured at the specified frame rates and exposure times in a producer-consumer architecture and saved on a solid-state hard drive inside the controlling PC.

The output of the cameras is stored in raw format as a .tiff image so that any required demosaicing of the colour channels can take place later, rather than being done on board the camera.

3 EQUIPMENT

3.1 Spectrometer

In order to measure the spectral output of the illumination sources used in this experiment, as well as the performance of the filters, a Thorlabs CCS200/M Spectrometer was used in conjunction with a linear-to-round fibre bundle cable to increase the signal-to-noise ratio. The average of 100 spectral measurements was taken for each spectra presented.

3.2 Bandpass filter

As PSP measurements require spectral separation of the excitation and emission signals, filters were required on the lenses of the cameras. The filters used in this experiment were bandpass filters (manufactured by Galvoptics, Basildon, United Kingdom) which were mounted on the front of the lenses. Given the PSP spectra shown in Figure 2, the filter used had a cut-on wavelength of 500 nm and a cut-off wavelength of 700 nm. This filter is ideal for PSP experiments, as it has an optical density (OD) of $OD = 3\sim4$ in the rejection bands and a transmission of $T > 80\%$ in the pass band. The spectral transmission of the filter is shown below in Figure 4, demonstrating its suitability for this experiment. As the cameras used vary in size and therefore lens mount, two different filters were required: one for the C-mount lenses and one for the S-mount lens. These filters were made of the same material and have the same spectral characteristics.

Figure 4. Galvoptics binary PSP filter spectra

The bandpass filter described in section 3.2 was affixed to the front of the lenses using an in-house-designed 3D-printed filter holder with grub screws to lock on to the lens.

3.3 Lights

Illumination for the linearity and SNR tests came from a modified laptop display powered by a stable, digital bench power supply. The display had the LCD removed and the internal circuitry was stripped back to the light controller. On board the laptop, the display brightness was originally controlled via pulse width modulation (PWM); however, the PWM circuitry was replaced with a current-limiting resistor and a stable, digital DC power supply which could be programmed to set voltages and currents.

Illumination for the PSP measurements came from the same in-house-built UV LED array used by Quinn et al. [13] which was made up of 144 Bivar 395 nm UV LEDs. As this light does not contain any temperature control or forced cooling, it was left to settle to a running temperature at a fixed voltage before PSP data acquisition began. During this time the PSP sample was not exposed to the light, in order to avoid excessive photodegradation.

The spectrum of the LED lights was measured using the spectrometer to ascertain if there was any significant output in the red part of the spectrum (a common issue with high-power UV LEDs). Figure 5 shows that there is very little output in the red region of the spectrum (approximately 500 times lower in magnitude than the 395 nm UV peak), making these lights suitable for PSP measurements. As these lights are custom-made and the binary PSP technique acquires reference conditions at the same time as test conditions, these lamps can be made to fit into any space and produce distributed lighting over specified areas.

Figure 5. UV LED lamp spectrum

3.4 Calibration chamber

This system consists of an in-house-designed pressure chamber with a quartz glass window and a thermoelectric Peltier element, as shown in Figure 6.

Figure 6. PSP calibration chamber

The pressure was controlled using a GE Druck Pace5000 pressure controller which, given a negative and positive pressure input, can control pressure with an accuracy of ± 22 Pa over a range of 0–3.5 bar absolute. The repeatability of the pressure controller is to within the same accuracy (± 22 Pa). Temperature was measured using a K-type thermocouple and an AD594 amplifier connected to a differential measurement channel of a National Instruments myRIO. The Peltier element was controlled using a standard lab power supply and an H-bridge stepper motor controller (allowing current to be driven forwards or backwards through the Peltier). The H-bridge was controlled via the myRIO, leading to a closed-loop temperature controller capable of maintaining the temperature within the chamber to within ± 0.1 K of the desired value.

3.5 PSP sample

An aluminium plate was cleaned with acetone and then sprayed with a matte white paint before being over-sprayed with ISSI BinaryFIB PSP [14] using a modeller's airbrush. Other formulations of this paint are available for different applications.

The sample was then baked in an oven to drive off moisture and evaporate the solvents used in the paint. The PSP sample was placed in the calibration chamber and held in contact with the Peltier device with heatsink paste to ensure good thermal conductivity.

4 METHODOLOGY

This section describes the testing procedure and optical conditions for each of the experiments conducted. For every test conducted, the cameras were left acquiring (but not saving) images for approximately five minutes to ensure they had reached thermal equilibrium before measurements were conducted. Any lighting used was also left activated during this time.

4.1 Camera benchmarking

In order to measure the camera performance parameters, images were taken with no objective lenses fitted. This avoided any vignetting effects that can be caused by machine-vision lenses (particularly S-mount lenses).

4.1.1 Temporal stability

Measurements of temporal stability were taken by capturing 1000 dark images and calculating the response over time of what should be a constant signal. For these images, a body cap was fitted and the cameras were placed in a dark environment. All cameras had 10 ms exposure times and the data was recorded at the maximum acquisition rate. The average value for each colour channel was extracted from each image captured and plotted out over time to see if there were any significant trends, which might imply the camera had heated up during acquisition and increased its dark value.

4.1.2 Linearity

In order to measure the linearity of the cameras, the LCD backlight screen was set to a fixed power and the camera exposure times were modified according to the average histogram value. A target histogram value of 95% was used to set the upper limit of exposure and the exposure time was systematically reduced from this value. The AT200GE camera started at 14 ms exposure for each channel and was reduced by 0.5 ms until the camera's minimum exposure was reached.

The ISSI PSP CCD camera exposure was set to 10 ms, which was the maximum exposure for the green channel; this value was then reduced in 0.5 ms steps. At 10 ms exposure, the red channel histogram was at approximately 60% of the dynamic range of the chip. In order to avoid any pixel bleed from saturated green channel pixels, it was decided not to expose the camera for longer as doing so may have affected the linearity results. The opposite was true for the Basler Ace, Genie Nano and Ximea XiMu as these cameras had saturated green channels at approximately 60% of the red channel at a 10 ms exposure time (this value varies by camera and is likely dependent on the Bayer filter pass bands). A more monochrome light source would have allowed for the complete exposure range to be estimated for both channels; however, given that this is a Bayer filter camera, measurements across the green channel range are sufficient to demonstrate the camera's suitability.

For each measurement, 30 images were captured and averaged to give a final image for each condition.

4.1.3 Signal-to-noise ratio

In order to estimate the SNR of each camera, the LCD backlight was set at two different powers to give histogram values of approximately 85% and 50% of the dynamic range of each chip with no saturated pixels. The AT200GE exposure times were 14 ms for both red and green channels; this resulted in balanced exposures between the channels. The ISSI PSP CCD camera had a 12 ms exposure for the green channel and the experiment was repeated for the red channel independently with an exposure time of 18 ms. The other three cameras used 10 ms exposure time with varying light power, with the experiment being repeated for red and green channels independently.

For both conditions described, 100 images were captured and estimates of SNR made using the same method described by Quinn et al. [11].

4.2 Colour cross-talk

In order to estimate the effect of colour cross-talk, the quantum efficiency curves shown in Figure 3 were interpolated to fixed wavelength increments (0.5 nm) and the spectral output of the PSP (Figure 2) was interpolated to the same increments. The two spectra were multiplied together and numerically integrated to give an estimate of the exposure value. Using this method, it is possible to estimate the suitability and temperature-sensitivity of the measurements taken by that camera *a priori*.

4.3 PSP calibration

All cameras with standard C-mount fittings used a 50 mm F2.0 Kowa lens, while the Ximea XiMU used a 1.8 mm F1.8 S-mount lens with a locking ring to secure focus.

The temperatures investigated were 273, 293 and 313 K. Temperature was set and left to settle for 30 seconds once it was within the 0.1 K tolerance to that ensure the temperature was completely uniform across the aluminium test piece. For a given temperature, a pressure sweep was conducted from 10 kPa to 150 kPa (absolute) in 10 kPa steps.

Once each condition had been reached (settling time was less than 30 seconds for each condition), 30 PSP images were taken and stored on the controlling PC. The exposure levels used were set according to the lowest temperature and pressure condition, as this yields the brightest PSP output.

The 30 images were averaged to produce a single image for each condition. For the Bayer cameras, the two green channels were averaged together before ratioing with the red channel images.

5 RESULTS AND DISCUSSION

This section describes the results of the tests conducted and draws conclusions.

5.1 Benchmarking

The camera-benchmarking tests produced similar results to those seen previously [11] and demonstrated that all of the cameras tested are suitable for PSP measurements.

5.1.1 Dark current

The ISSI PSP CCD camera has a maximum exposure time of 1/35 seconds (28ms) due to its fixed frame rate. As a result of this, only exposure values lower than this are shown.

Figure 7. Dark current camera performance: a) image dark value vs. log exposure time per channel and b) standard deviation across the dark image vs. log exposure time

The results shown in Figure 7 a) for the JAI AT200GE are broadly consistent with most small, uncooled cameras, in that increasing the exposure time increases the dark value reported by the camera. However, the results from the ISSI PSP CCD, JAI AT200GE and even the Genie Nano show excellent stability, something that would only be expected from a cooled camera. It is worth noting that the values presented in this figure are the raw values and have not been scaled according to the range of each camera. Given that the JAI AT200GE has a 10-bit ADC and all other cameras have a 12-bit range, in order to compare all cameras over the same range, the JAI AT200GE values should be multiplied by four.

Typical exposure times for PSP testing are of the order of milliseconds up to tens of milliseconds. Given that the dark values and standard deviations barely change for either camera in this region, it is safe to assume that the dark value can be taken as a constant offset. The same is also true of all the other machine vision cameras shown in this figure. A constant offset is sufficient over the likely range of exposures.

5.1.2 Temporal stability

The variation in dark current for each of the cameras tested is shown in Figure 8. There are no significant trends across the images taken with the exception of the Basler Ace camera which shows an increase from approximately 6 to 10 counts over the course of 1000 exposures. This increase could be significant if very small pressure changes are to be resolved; however, by careful control the acquisition settings, this error can be minimised.

Figure 8. Variation in dark current with number of images taken for all cameras

5.1.3 Linearity

All cameras reported good linearity values across a wide range of exposures, as can be seen in Figure 9 a). In accordance with the EMVA1228 guidelines [15], only the exposure values from 5-95% (where possible) were used in the estimation on non-linearity. The calculated values of non-linearity were:

- Ace – Green 0.83%, Red 1.19%
- AT200GE – Green 0.89%, Red 0.98%
- ISSI PSP CCD – Green 0.68%, Red 0.29%
- Nano – Green 0.87%, Red 0.44%
- XiMu – Green 0.92%, Red 0.90%

The values of non-linearity reported here show that most of the cameras are suitable for this purpose with the possible exception of the Basler Ace. A value of non-linearity of 1.19% is significant when taking quantitative measurements.

Figure 9 b) shows the deviation from the linear fit (i.e. the residual) for each camera and colour channel according to the legend in Figure 9 a). This shows that for some cameras (particularly the XiMu camera) there is a periodic variation from one exposure to the next. This implies that the exposure time set is not the exact value requested and used when producing a linear fit. As a result of this the values for non-linearity shown here should be taken as a worst case scenario as it is likely that for varying intensity in a scene (for a fixed exposure), the response will be more linear than varying exposure time.

5.1.4 Signal-to-noise ratio

Figure 10. Signal-to-noise ratio for all cameras at a) 50% saturation and b) 85% saturation

The SNR values shown in Figure 10 are consistent with machine vision cameras which are not cooled but are still high enough to enable quantitative measurements. All cameras show little dependency (only 2 dB) of SNR to exposure level. This is reduced even further when multiple images are averaged and the values asymptotically reach their maximums. The rate at which the cameras reach their maximum values is increased with increasing signal level; however, this is not as pronounced for these cameras compared to those tested by Quinn et al. [11]. The performance of the colour Ace, Nano and XiMu cameras is comparable to their monochrome counterparts, as would be expected.

The measurement of SNR for these cameras was conducted independently for red and green channels as a broadband light source was used. The reason for this is detailed in section 4.1.2. There is a clear and repeatable offset between the red and green channels in terms of SNR which varies between camera manufacturers.

5.2 Camera alignment

As noted in the study by Hijazi et al. [17], when using three-CCD cameras there is never perfect alignment between each of the individual CCD sensors. This is undetectable to the naked eye; however, it could cause edge artefacts when calculating image ratios. In order to estimate the significance of this effect, an image of a speckle pattern was taken using the JAI AT200GE camera and the colour channels (green and red) were cross correlated with each other in the PIV software DaVis from LaVision. The output, shown in Figure 11, illustrates that the two images are different from each other in magnification rather than any simple bulk displacement. The vector direction indicates the displacement direction calculated by DaVis and the colour represents the magnitude. As the displacements are all significantly less than one pixel, it was decided not to correct for this aberration.

Figure 11. Vector displacement field between red and green images of AT200GE as calculated using DaVis PIV software

5.3 Demonstration of suitability

In order to demonstrate the suitability of the cameras for such measurements, as well as to estimate the expected colour cross-talk, the PSP spectrometer results at a constant temperature of 293K were interpolated to the same wavelength intervals as the digitised data from the camera datasheets for the colour channel QE. This allowed for integration of the expected signal in each of the channels at every condition and allowed for calculation of the expected change in the green channel (ideally pressure-insensitive) to changes in pressure. The green-channel response was estimated by integrating from 400 to 600 nm wavelength after multiplying by the normalised response of the bandpass filter.

Figure 12 shows the estimated percentage change in the green-channel output based on the measured PSP spectra and the interpolated camera QE curves. As would be expected, the camera with the lowest colour cross-talk (JAI AT200GE) showed almost exact correlation with the spectrometer results. The ISSI PSP CCD showed little change in the green-channel response as the pressure was increased, demonstrating that, given the spectral output of the PSP and the levels of overlap between the colour channels, this camera is very suitable for this kind of measurement. The small machine vision cameras showed significantly larger changes in the green-channel response, which is solely due to the relatively large response of the green channel around the 700 nm region; this result implies that these cameras are less suitable for two-component PSP measurements. However, as will be seen in subsequent sections, the effect of this on PSP results is not as straightforward as it might first appear.

Figure 12. Estimated percentage change in green-channel output due to pressure

5.4 Comparison of cameras

Figure 13. Measured percentage change in green-channel output due to pressure

The measured values of change in the green-channel response due to pressure at a constant temperature (293K) are shown in Figure 13. As would be expected from the estimated results in Figure 12, the three-CCD camera shows the best performance in this region, with the ISSI PSP CCD camera a close second. It is interesting to note that the Genie Nano camera performed significantly worse in this area than would have been expected from the quantum-efficiency estimates digitised from the datasheet. Despite this, subsequent sections (5.7 in particular) demonstrate that this camera, and the other machine vision cameras, are still suitable for this type of PSP measurement and in some circumstances can even give superior results, as detailed in the conclusion.

5.5 Binary PSP measurements

All of the cameras performed well in calibration measurements using binary PSP, as can be seen in their individual calibration curves shown in Figure 14. The results shown in this figure are the result of equation 2. All of the cameras show a significantly reduced temperature sensitivity compared to single-component PSP measurements. Each of the cameras demonstrate the standard PSP calibration curve trend, in that the response is significantly larger at lower pressures. All of the PSP responses show a non-linear calibration curve over wide pressure ranges, identical to that found on the binary PSP datasheet [14].

Figure 14. Binary PSP calibration of a) Basler ACE, b) JAI AT200GE, c) ISSI PSP CCD, d) Genie Nano and e) Ximea XiMU

In order to compare the relative performance of the cameras, Figure 15 shows the five cameras' calibration curves at each temperature plotted against each other. From this figure there is a distinction between the small machine vision cameras and the AT200GE and ISSI PSP CCD cameras. The AT200GE and ISSI PSP CCD have significantly higher pressure sensitivity; this is discussed in more detail in the following sections.

Figure 15. Binary PSP Calibrations at a) 273 K, b) 293 K, and c) 313K

5.6 Pressure sensitivity

The pressure sensitivity as measured by the cameras is estimated by taking the difference between subsequent values of equation 2 and dividing them by the difference in pressure (10 kPa) at a fixed temperature of 293 K. These values were then scaled as a percentage. The results in Figure 16 show that the cameras with lowest colour cross-talk have the highest pressure sensitivity. This finding is due to the fact that their individual channels are measuring less from the other channels, meaning they have a lower bias offset. The values reported here are in line with (albeit slightly lower than) the values from the PSP datasheet [14], quoted as 0.6% per kPa at 293 K. However, this could be due to numerous factors, such as spraying technique or humidity. The reduction in sensitivity as overall pressure increases is a common factor of PSP [13].

Figure 16. Pressure sensitivity as percentage change in output per kPa for all cameras at 293K

5.7 Temperature sensitivity

Figure 17. Temperature sensitivity as percentage change in output per K across the pressure range

Figure 17 shows the measured temperature sensitivity, which is calculated by using a linear least-squares curve fit between the calibration curve points at a fixed pressure for each camera (as shown in Figure 14) and calculating its gradient due to temperature. All of the cameras demonstrate a relatively similar level of temperature sensitivity. The quoted values for temperature sensitivity for this paint is 0.03% per degree, which is of the same order as the findings of this study, albeit slightly lower. Despite this, all of the values shown here are at least one order better than the measured temperature sensitivity of the UniFIB single-component PSP measured by Quinn et al. [11], highlighting the significant improvement in temperature sensitivity achieved using binary PSP.

Spectrometer measurements are included in Figure 17 and were estimated by integrating the results from the spectrometer between 400 and 600 nm for the green channel and between 600 and 800 nm for the red channel (after a multiplication by the normalised filter performance curve). The spectrometer response shows a broadly similar temperature response at low pressures but is significantly reduced as the pressure is increased, a much more pronounced version of that seen by the cameras.

It is interesting to note that the cameras exhibiting the highest temperature sensitivity are the two larger and most expensive models: the JAI AT200GE and the ISSI PSP CCD. This is likely due to their much more exact colour separation. Figure 2 shows that the change in intensity due to pressure is much greater than that due to temperature. As the change in the green channel is not of the same magnitude as the red channel, separating out the colours exactly may not actually give the lowest temperature sensitivity for binary PSP experiments.

Figure 18. Temperature sensitivity at various separator wavelengths integrated from spectrometer results

In order to estimate the best point at which to separate the pressure-sensitive and pressure-insensitive parts of the PSP response, the PSP spectra shown in Figure 2 were integrated to create a *green* and *red* value with different separating wavelengths, as shown in Figure 18. In this figure, the temperature sensitivity is estimated in the same way as it is for the PSP data in Figure 17; however, the wavelength at which the green and red images were split out from the continuous spectrum is given in the legend. From this figure, it can be seen that the lowest temperature sensitivity (i.e. the best result) is given by approximately 570 to 580 nm. This figure serves as a guide as to how to choose the best camera and filter combination for binary PSP acquisition; however, it does assume that the response of the colour channels is completely independent (something that is clearly not true for the majority of cameras, as shown in Figure 3).

5.8 Uncertainty analysis

In order to quantify the uncertainty in the measurements shown, a linear calibration (equation 2) was fitted across a small pressure change, 90-100 kPa (as is commonly done in low-speed PSP measurements). The errors in the calibration coefficients A and B were estimated by propagating uncertainties of parameters used in their calculation (intensity ratio, pressure and their response to temperature).

The standard deviation of the 90 kPa-averaged image, divided by the reference condition (100 kPa) at 293 K, was calculated over an area of the PSP (which should ideally be uniform) and was scaled to give 95% confidence. Uncertainties in temperature control of 0.2 K were assumed given the response of the thermocouple. It is unlikely that the measurement is that accurate, but it is likely to be that stable and repeatable. A pressure uncertainty of 22 Pa was assumed based on the manufacturer's datasheet. Also, the sensitivity of the coefficients A and B to temperature was estimated by using a least-squares linear fit between the calibration curves for each temperature at the given point and calculating the gradient, representing their sensitivity coefficients. These values were then multiplied by the assumed uncertainty in temperature. Finally, all the values were added together using the root-sum square method [18].

The uncertainty estimates are shown in Table 2. The dominant experimental uncertainty by two orders of magnitude is the sensitivity of A and B to the measured intensity ratio and its variability. Any effects due to temperature are significantly lower than for single-component PSP measurements [11], thanks in part to the improved calibration chamber, but mainly due to the significantly lower temperature response of the binary PSP.

Table 2. Uncertainty in calibration parameters

Camera	A	B
Ace	± 0.0050	± 0.0098
AT200GE	± 0.0059	± 0.0116
ISSI CCD	± 0.0039	± 0.0076
Nano	± 0.0037	± 0.0073
XiMU	± 0.0074	± 0.0145

Given that the uncertainty calculation is dominated by the image noise rather than any other component, taking more images and averaging them (provided that it is cost-effective to do so) should produce the best PSP data.

6 CONCLUSIONS

This study has aimed to demonstrate the suitability of inexpensive, off-the-shelf machine vision cameras for binary PSP measurements based on colour-channel separation. Successful calibrations of binary PSP were conducted for all of the cameras described here, demonstrating that small, cheap cameras can be used to conduct such measurements. This opens up the possibility of temperature-compensated PSP measurements being conducted on board real vehicles or in confined spaces within models. This work has direct applicability to intake aerodynamics, where large pressure and temperature changes are present in confined spaces.

The temperature sensitivity of the binary PSP can be reduced by correctly selecting the camera with the most suitable spectral overlap. This could increase the range of applicability of such measurements as certain cameras give lower temperature sensitivities than would be traditionally expected.

In addition to the first successful trial of miniature colour cameras for binary PSP testing, the relationship between colour separation and temperature sensitivity has been investigated and an optimal separation wavelength has been found, along with a method of predicting the response of different cameras using spectral interpolation and integration.

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