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Title	A novel image processing-based system for turbidity measurement in domestic and industrial wastewater
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Publication Date	2018-01-19
Publication Information	Mullins, Darragh, Coburn, Derek, Hannon, Louise, Jones, Edward, Clifford, Eoghan, & Glavin, Martin. (2018). A novel image processing-based system for turbidity measurement in domestic and industrial wastewater. <i>Water Science and Technology</i> , 77(5), 1469-1482. doi: 10.2166/wst.2018.030
Publisher	IWA Publishing
Link to publisher's version	https://doi.org/10.2166/wst.2018.030
Item record	http://hdl.handle.net/10379/15289
DOI	http://dx.doi.org/10.2166/wst.2018.030

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A novel image processing-based system for turbidity measurement in domestic and industrial waste-water.

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Abstract

Wastewater treatment facilities are continually challenged to meet both environmental regulations and reduce running costs (particularly energy and staffing costs). Improving the efficiency of operational monitoring at wastewater treatment plants (WWTPs) requires the development and implementation of appropriate performance metrics; particularly those that are easily measured, strongly correlate to WWTP performance, and can be easily automated, with a minimal amount of maintenance or intervention by human operators.

Turbidity is the measure of the relative clarity of a fluid. It is an expression of the optical property that causes light to be scattered and absorbed by fine particles in suspension, (rather than transmitted with no change in direction or flux level through a fluid sample). In wastewater treatment, turbidity is often used as an indicator of effluent quality, rather than an absolute performance metric, although correlations have been found between turbidity and suspended solids. Existing laboratory-based methods to measure turbidity for WWTPs, while relatively simple, require human intervention and are labour intensive. Automated systems for on-site measuring of wastewater effluent turbidity are not commonly used, while those present are largely based on submerged sensors that require regular cleaning and calibration due to fouling from particulate matter in fluids.

This paper presents a novel, automated system for estimating fluid turbidity. Effluent samples are imaged such that the light absorption characteristic is highlighted as a function of fluid depth and computer vision processing techniques are used to quantify this characteristic. Results from the proposed system were compared with results from established laboratory-based methods and were found to be comparable. Tests were conducted using both synthetic dairy wastewater and effluent from multiple WWTPs, both municipal and industrial.

This system has an advantage over current methods as it provides a multipoint analysis that can be easily repeated for large volumes of wastewater effluent. Although the system was specifically designed and tested for wastewater treatment applications, it could have applications such as in drinking water treatment, and in other areas where fluid turbidity is an important measurement.

Keywords

Wastewater Treatment, Turbidity, Performance and Monitoring, Real-time monitoring, Sensor, Light-based sensor

Introduction

Water and wastewater quality monitoring and assessment is an ongoing area of research that has been seen continual development over the last 20 – 30 years (Council of the European Communities, 1991; Métadier and Bertrand-Krajewski, 2012; European Union, 2014). Given the amount of energy consumed in the water/wastewater treatment sector, there is a need to improve monitoring and control procedures for the operation of treatment plants, to allow them to dynamically optimise their energy consumption based on the loading at any given time, rather than being permanently configured for maximum loading conditions or for worst case scenarios (Luccarini et al., 2010). Ongoing operation and performance monitoring of wastewater treatment plants (WWTPs) is a particular problem for small to medium scale plants, particularly those lacking full-time staff (Singh et al., 2015). Infrequent monitoring limits data availability, which can in turn hinder effective management of WWTPs (Torregrossa et al., 2016). While compliance monitoring is generally performed on a regular basis to report common WWTP discharge parameters, such as 5-day biochemical oxygen demand (BOD₅), chemical oxygen demand (COD), suspended solids, ammonia, total phosphorus, orthophosphate and total nitrogen to regulatory bodies, such monitoring tends to be infrequent (e.g. monthly) (Environmental Protection Agency, 2014; Hannon, 2016; Doherty et al., 2017). This paper presents one solution to address this issue: a novel technique for determining turbidity, demonstrated using samples from effluent streams from case-study WWTPs. The proposed method was implemented using image processing and novel imaging techniques that show light absorption as a function of fluid depth. Such a system could be used in tandem with current measurements performed for compliance monitoring to meet discharge regulations imposed on a European level (European Commission, 1998), and a centralised data management system (O'Donovan et al., 2015) to provide operational information on a more regular timescale.

Turbidity in fluids

Turbidity (the cloudiness of a fluid caused by suspended particles) is one of the simplest measurements associated with suspended particles in a fluid, and it is widely used as a general indicator of performance in water & wastewater treatment systems (Bertrand-Krajewski, 2004; Arévalo et al., 2009; Bakker et al., 2014; Castaño and Higuera, 2016). However, in many cases, measurement procedures are not always conducted as outlined by the Standard Methods (Hannon et al., 2014; Doherty et al., 2017).

Turbidity is also an important factor in sectors other than wastewater treatment. For example some marine applications of turbidity include: using turbidity to examine the environmental effects of dredging (Pennekamp et al., 1996; Shafer et al., 2016) and the effects of turbidity on fish and other aquatic life (Cyrus and Blaber, 1987; Dayton et al., 1995; Suedel and Wilkens, 2017). Turbidity is also utilised in the pharmaceutical industry to monitor the rate of emulsification of drugs (Patel et al., 2010).

While turbidity is predominantly caused by suspended sediment such as silt, as well as organic materials such as algae, there can also be coloured dissolved organic matter (DOM) present which causes discoloration. The colour can vary depending on the source. Green, yellow and brown hues are the most common in wastewater effluents and in a small number of cases, mainly in industrial wastewater treatment, the effluent sample can appear orange in colour. In marine applications, humic stain refers to the tea colour produced from decaying organic matter underwater due to the release of tannins (Stedmon et al., 2003; Murphy et al., 2010). This DOM is another key area of research where analysis of the

absorption and fluorescence of DOM at different wavelengths is leading to the development of new sensor technologies (Hambly et al., 2015; Logue et al., 2016).

Turbidity as a surrogate measurement for WWTP performance

While turbidity measurements are not included in the compliance monitoring guidelines imposed by the European Council (Council of the European Communities, 1991) it is a useful surrogate for other performance parameters. Cloudy effluent samples can indicate poor process control or a problem within the treatment system e.g. poor settling in the clarifier could be indicated by a higher turbidity measurement in the effluent. A key test which is used widely to inform operational decisions at WWTPs is the measurement of Sludge Volume Index (SVI). In this test, mixed liquor from the aeration tank is left to settle in a standardised vessel for a set time period and the resultant Settled Sludge Volume (SSV) is recorded. This is then used in conjunction with the Mixed Liquor Suspended Solids (MLSS) measurement to determine SVI. When determining SSV, the turbidity of the supernatant left after the sludge has settled can also be indicative of the effluent turbidity (Hannon, 2016).

Total suspended solids (TSS) of the wastewater effluent, a measure of the mass of particulate matter in a fluid, has also been found to correlate with turbidity (Pfannkuche and Schmidt, 2003; Mels et al., 2004; Minella et al., 2008; Métadier and Bertrand-Krajewski, 2012; Hannouche et al., 2017). TSS is a significant quality metric in wastewater treatment and a good indicator of other pollutants, particularly nutrients and metals that are carried on the surface of sediment in suspension (Packman et al., 1999). An increase in turbidity in the effluent stream generally indicates an increase in TSS. Using linear regression and site-specific calibration, an estimate of TSS (normally a labour-intensive measurement) can be made from a relatively quick and easy turbidity measurement (Bertrand-Krajewski, 2004). This relationship between turbidity and other wastewater effluent properties such as particle size distribution (PSD) can quickly provide more useful information about WWTPs for performance monitoring. PSD has been found to have a significant influence on turbidity as well as TSS and COD (Wu et al., 2009; García-Mesa et al., 2010; Bersinger et al., 2015). The latter study by Wu et al highlights the inverse relationship between particle size and turbidity. On the other hand, TSS was found to be highly correlated with the volume of particles, with the larger particles being the biggest contributor to volume. Furthermore, multiple studies have also established the relationship between infrared spectroscopy and COD, BOD and TSS (Páscoa et al., 2008; Yang et al., 2009; Mesquita et al., 2017). Building upon these relationships a turbidity monitoring system could provide useful information on WWTP performance.

Turbidity in water treatment

Turbidity monitoring requirements are specified in the drinking water treatment directive, that states the minimum acceptable error of 25 % for the measurement of turbidity (The Council of European Union, 1998; European Union, 2014). In drinking water treatment systems, the presence of dissolved light-absorbing substances such as tannins can cause discoloration and cloudiness of the water supply which can indicate poor water quality. These dissolved substances may be too small to be counted in a suspended solids calculation, but they do contribute to turbidity as they affect water clarity. While dissolved matter is not included in TSS measurements, it can cause artificially low turbidity readings as it absorbs light instead of scattering it (Stedmon et al., 2003; Gitelson et al., 2008).

Turbidity has also been found to affect the efficiency of chlorination in drinking water disinfection. Particulates in drinking water supplies can act as carriers for bacteria, heavy

metals, and pesticides. While turbidity does not provide a direct measure of the levels of these other potentially harmful impurities, its presence highlights the fact that a viable mechanism exists for carrying them into the drinking water supply (LeChevallier et al., 1981; Haydar et al., 2009; The Environmental Protection Agency, 2009).

Current turbidity measuring technology

A number of systems are currently available for estimating fluid turbidity in general, ranging from fully automated systems that measure the attenuation of light in a fluid such as spectrophotometers, or more specifically turbidimeters, to more subjective measurements of the depth of fluid through which a target can no longer be seen i.e. the Secchi Disc (Gregory, 1998). There are multiple units of turbidity defined; the two most commonly used being (i) NTU (Nephelometric Turbidity Units), (ii) FAU (Formazin Attenuation Units). The main difference between NTU and FAU is the method by which the measurement is conducted (Telesnicki and Goldberg, 1995). To generate NTU, the instrument measures scattered light from the sample at a 90° angle to the incident light. The Standard Methods for the Examination of Water and Wastewater specifies the use of NTU (APHA, 2005). While an instrument that generates FAU measures the decrease in transmitted light through the sample at an angle of 180° to the incident light; this type of measurement is often made using a spectrophotometer or colorimeter. Laboratory based turbidity measurements are generally performed using a spectrophotometer or dedicated turbidimeters and require manual intervention. Turbidity is calculated by comparing the attenuation of the sample to that of deionised water (Melik and Fogler, 1983)). Turbidimeters are deployed on-site at treatment plants, but prolonged submersion in the turbid fluids can lead to build up of organic material on the sensors, reducing their accuracy.

A pilot-scale automated system that monitors treated water by measuring the refractive index of the effluent stream has been tested in small scale applications and was demonstrated to accurately detect water quality issues such as turbidity in a water distribution network (de Graaf et al., 2012; Williamson et al., 2014).

Current automated solutions require regular cleaning and calibration as the sensor fouls due to the build-up of particulate matter; this is particularly an issue in the wastewater sector (Joannis et al., 2008). While it may be feasible to deploy existing automated systems in larger plants with technicians onsite regularly, this is not always possible in small to medium-scale treatment plants where monitoring is less frequent. Therefore, due to a lack of calibration, results from submerged turbidity sensors are rarely deemed trustworthy after more than a few days. However, in ideal conditions, where the sensors are regularly cleaned and calibrated, they can yield a reliable and accurate estimate of turbidity.

Proposed Solution

This paper proposes a novel automated system for estimating turbidity, by using readily available digital cameras, specific lighting and imaging conditions, together with image processing techniques. The proposed system is tested with several effluent samples and the results presented. The concept for the image processing based turbidity estimation system builds and improves on two of the state of the art methods for turbidity measurement currently in use in water/wastewater treatment industry. The proposed system removes the need for manual observation methods that operators often use to estimate turbidity in WWTP effluent streams as an informal assessment of performance (Hannon, 2016). Instead, it replaces this manual process by using inexpensive off-the-shelf digital camera technology, and implementing similar lighting to the spectrophotometer to measure the attenuation of light through the sample medium.

Methods

Sample collection

For this case study, two different and independent datasets were examined. Firstly, 5 wastewater effluent samples were collected from 5 different municipal WWTPs. To increase the dataset size, these were then mixed together in various proportions and also diluted to give 16 different turbidity values for analysis. These mixed effluent samples varied in turbidity from 10 FAU to 250 FAU, as measured by the spectrophotometer. A minimum volume of 5 L of effluent was collected at each sampling event to best ensure that the sample analysed was representative. The collected samples were transported to the laboratory for immediate testing or refrigerated at 11°C for use within 48 hours.

A second dataset was recorded using synthetic wastewater from a laboratory-scale dairy wastewater treatment system. These samples were taken over a 3-day period and diluted two-fold, in the case of a high turbidity, to yield more data points for analysis. The sample size for this dataset was 15 and the turbidity values ranged from 30 to 140 FAU, as measured by the spectrophotometer.

Prior to use or decanting to a smaller vessel, the sample storage container was inverted a number of times to ensure homogeneity of the sample and to negate the effects of any settlement during transport or storage.

Control Results

For validation of the proposed system, all results were compared to turbidity measurements made using a calibrated spectrophotometer manufactured by Hach (Model: DR2010). A spectrophotometer was chosen because the process of performing the test is robust, repeatable and the results were based on a deionised water standard that is readily available. The spectrophotometer was calibrated as per manufacturer's specifications for turbidity calculations, and the wavelength of light of the spectrophotometer used in the experiments was 860 nm. Two samples were taken for each turbidity level and tests were conducted in triplicate to reduce experimental error and to examine the standard deviation. To gauge the standard level of acceptable error, a set of initial samples were prepared with a range of known concentrations of bentonite as a substitute for natural particulate.

Table 1 shows the results from the initial spectrophotometer tests with bentonite. For this test, the turbidity of two 20 mL samples was measured six times i.e. three times each, with the vessel being agitated between each measurement to ensure the particulate stayed in suspension. A fresh test tube was used for each sample. As can be seen from the results, the standard deviation was less than 10 FAU. However, the percentage deviation is a more significant statistic: in this case they were within acceptable tolerances, based on the required precision of 25% for water turbidity monitoring outlined in EU legislation (European Union, 2014).

Table 1. Bentonite Spectrophotometer Turbidity Results

Sample Name	Mean (FAU)	Standard Deviation	Percentage Deviation (%)
a	10	1	10
b	44	5	11
c	66	4	6
d	107	7	6
e	157	8	5
f	191	5	3

Imaging System and Lighting conditions

Effluent samples from the case-study WWTPs were imaged in a 4 L glass vessel as shown in Figure 1(a) (photographic view of the laboratory rig) & Figure 1(b) (schematic view of the rig). Samples were agitated by a magnetic stirrer placed in the vessel, thus ensuring the particles did not settle over the course of the test. To avoid any interference from environmental lighting, the test rig for data acquisition was surrounded by blackout material.

For this study, both orientations of the imaging sensor relative to the light source were examined, the orthogonal orientation was found to be more suitable for two reasons. Firstly, a reduction in the amount of light directed towards the camera allowed a wider range of exposures to be utilised without saturating the image sensor. Secondly, the geometry was such that light attenuation could be seen as a basic function of increasing fluid depth across the width of the image.

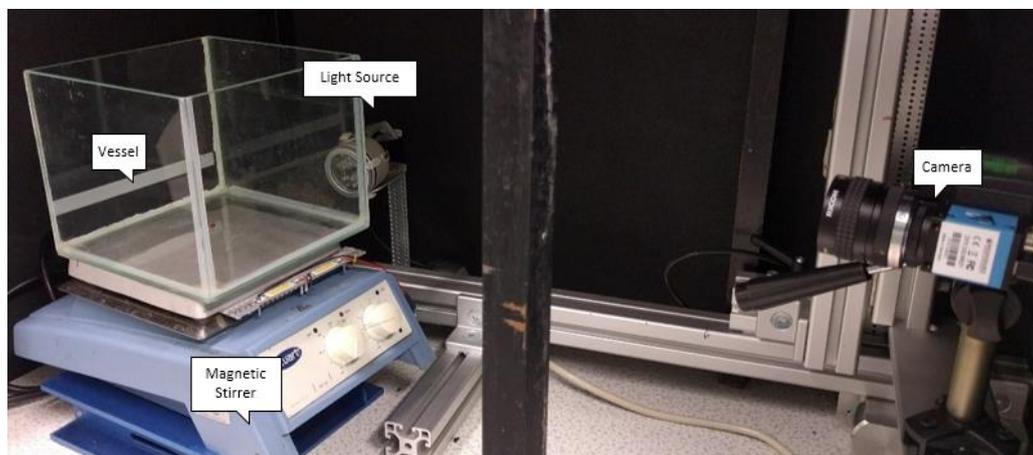


Figure 1(a). Test rig showing orientation of light source and camera relative to the vessel for effluent sample. Vessel is constructed from transparent glass and is placed on a magnetic stirrer for sample agitation.

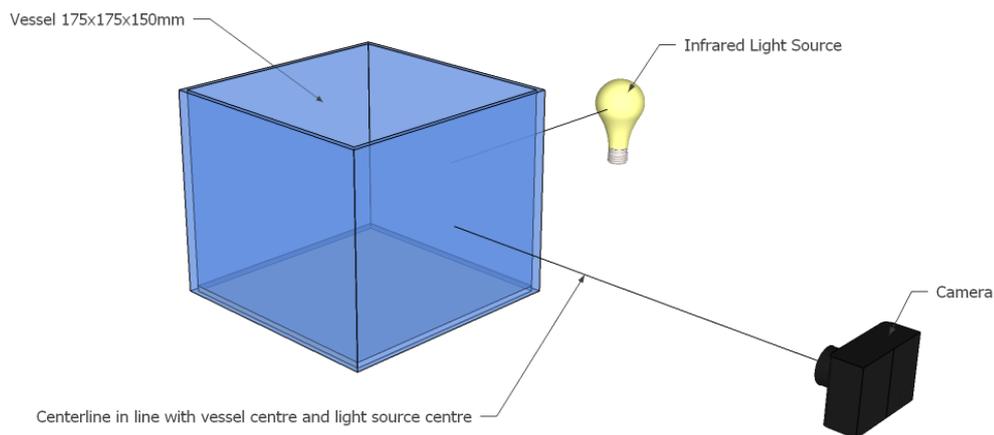


Figure 1(b). Schematic of test rig: imaging conducted under blackout material to avoid interference from ambient lighting. The magnetic stirrer is not shown

Illumination source wavelength

For turbidity measurements, the lab-based spectrophotometer used light in the infrared (IR) range (800 nm to 1 μ m). The wavelength was kept consistent to allow for comparison of spectrophotometer based measurements. The Hach spectrophotometer (DR2010) used for control measurements utilised a wavelength of 860 nm for measuring turbidity.

An IR light source was used because tannins (coloured particles that exhibit a hue), sometimes found in wastewater effluents, have different white-light absorption properties than non-coloured particles. IR light is not as sensitive to effluent sample colour, therefore it can be more suitable for wastewater treatment applications (Hongve and Åkesson, 1998), where effluent is not always clear and colourless.

Camera

A 1.2 MPixel monochrome CMOS (complementary metal-oxide semiconductor) camera (a DFK23UM021 camera manufactured by The Imaging Source) was used. The camera was controlled using a MATLAB script, allowing the capture setting to be controlled through software to image each sample at multiple exposures for multiple measurements of each sample. Three images were taken four seconds apart, at each of these exposures. Having multiple images of the target allowed for postprocessing to utilise averaging to minimise the effects of artefacts, such as bubbles or a large floc, that may corrupt the results. Therefore, for each sample, 12 measurements were taken, with a total image acquisition time of one minute per sample. The raw image data was saved as a lossless TIFF for further analysis.

The IR/UV cut filter was removed from the CMOS camera to allow the IR energy through to the imaging sensor. IR light sources generally have much lower light intensity than white light sources, so to avail of the full dynamic range of the sensor, exposure times 2 ms to 16 ms were utilised.

Image Analysis

Firstly, the region of interest (ROI) was defined to avoid the vessel structure. As shown in Figure 1(b), the vessel was illuminated from the right-hand-side, thus, this ROI began just

at the right-hand side wall and extended for the full width inside the vessel. The magnetic stirrer created areas of turbulent flow at the top and bottom of the vessel, therefore, the upper and lower limits of the ROI were defined to avoid these areas. The ROI was defined 150 pixels high and taken across the full width of the vessel, just above the centerline. The 150 pixel-high ROI was chosen to allow an average light intensity to be found across the vessel, this smooths the intensity profile. A value of 150 pixels was chosen as a relatively large proportion of the total volume (the total fluid height was 550 pixels), whilst avoiding the majority of the turbulent flow. The rows of the ROI were then averaged to give a single light intensity profile as a function of fluid depth. From this profile, an estimated turbidity value can be calculated, expressed in pixels, henceforth referred to as camera estimated turbidity (CET).

Examining this intensity profile, it was observed that the curve had a smooth, monotonic non-linear shape, the majority of it appearing exponential. Rather than applying any curve fit to each intensity profile, a simple single point comparison was found. Considering the light source as a step input to a black box system, the CET is an approximate measure of the fluid's step response (or time constant τ (tau)). CET was calculated from dark to light (left to right as shown in Figure 2), therefore the step response was defined as shown in (1). The CET of this intensity profile was then determined as the depth in pixels at which the intensity reduced to 63% of its maximum intensity.

$$\tau = 1 - \frac{1}{e} = 63.2\% \quad (1)$$

To find the CET for a given intensity profile, firstly 63% of the maximum intensity was found for each profile (Y value) and looping through the intensity profile values from low to high (left to right as shown in Figure 2), the CET was found as the X value where a horizontal line at this Y value intersects the intensity profile. These values were computed for the 3 images of each effluent sample taken at each exposure.

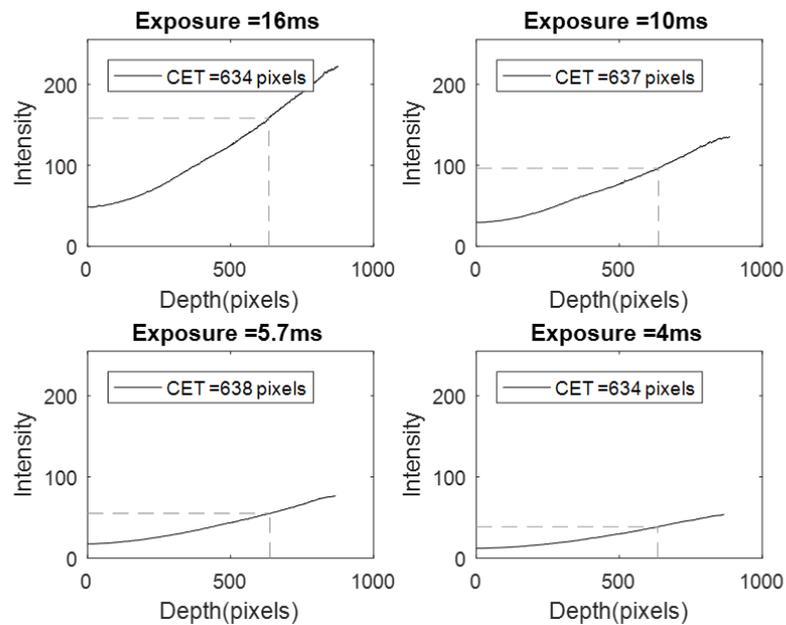


Figure 2. Intensity profiles for an 86 FAU effluent sample at 4 different exposure levels. CET measurement is indicated in dashed lines.

Examples of these intensity profiles and CET are shown in Figure 2 with the same effluent sample at four different exposures. The CET value was found to scale with exposure, provided the images were not saturated or under exposed. Municipal effluent samples with turbidity values less than 30 FAU, were found to be under exposed at 4ms exposure times, while images of samples with turbidity values greater than 250 FAU were found to be saturated at 16 ms exposure times. In between this range, there was an average standard deviation of 11 pixels across all samples in the 30-250 FAU range, equating to approximately 4 FAU. The standard error from the mean across 4 exposures was 10 pixels or approximately 3 FAU. This scaling of results with exposure highlights the robustness of the system.

Results

Figure 3 shows nine different effluent samples imaged at 16ms exposure, this CET value (on the X-axis) was then taken as the new turbidity measurement (as a function of depth which was measured in pixels). The light intensity was observed to decay from right to left. The inverse relationship between CET in pixels and turbidity in FAU can also be seen in the results.

The intensity profiles for samples with turbidity values of 32 and 72 FAU contained small discontinuities in the otherwise smooth decay of light intensity that were caused by floating matter in the effluent sample such as a floc or a bubble. These spikes in light intensity have the potential to give an erroneous CET value (usually a lower CET and subsequently a higher turbidity estimation when compared to comparable analyses using a spectrophotometer). This could present an issue if this spike in intensity coincided with the 63% threshold value used to calculate CET. However, the use of multiple images, in this case 3, allowed the intensity profiles to be averaged, and the effect of these spikes reduced, detection of these spikes is also an area for potential future work

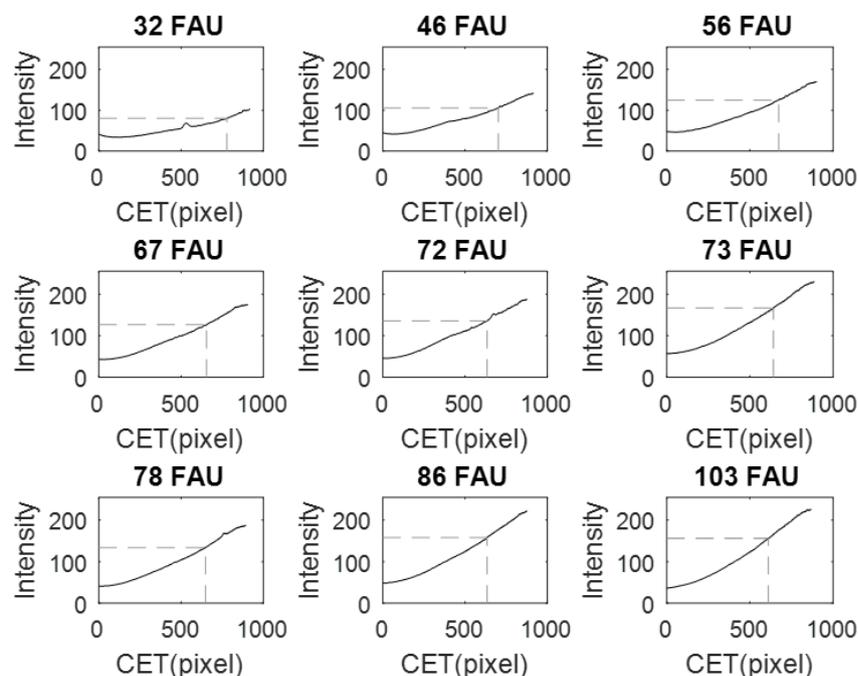


Figure 3. Range of samples varying in turbidity imaged at 16ms exposure. CET is indicated in dashed lines.

Conversion of results to FAU turbidity measurement.

For the proposed system to provide a turbidity measurement on the same scale (FAU) as the spectrophotometer, the CET was converted to a FAU turbidity value as follows: firstly, a turbidity value was measured for several water samples containing varying amounts of bentonite. These values were then correlated with the turbidity results from the spectrophotometer. Linear regression was used to find the line of best fit between the two data sets and the equation of this line used to convert CET in pixels to an FAU value (Figure 4). This conversion to FAU was first calibrated and then applied to independent bentonite samples tested for proof of concept. This calibration step is also required for different sample types e.g. synthetic, municipal and industrial wastewater to present the results on the FAU scale. For best results, 5-10 samples spread across the range of expected turbidity values from the WWTP would be required for calibration.

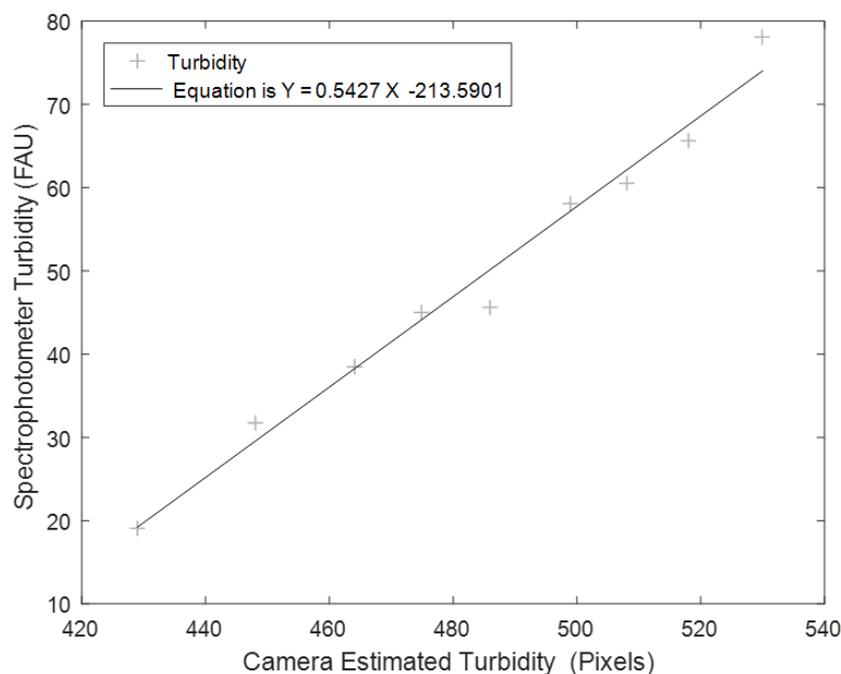


Figure 4. Calibration of the FAU calculation derived from the image processing system. X-axis is the CET, Y-Axis is the spectrophotometer turbidity measurement.

Statistical Agreement

The two data sets considered in this paper: (a) municipal wastewater effluent and (b) synthetic dairy effluent, were examined independently as they were found to have different light diffusion characteristics. The intensity of light, diffused towards the camera by synthetic dairy wastewater is greater than that for real effluent taken from the municipal WWTPs. The different composition and particle size distribution (PSD) of the two datasets were found to be the major reasons for the increase in light scattered by the synthetic wastewater. Smaller particles attenuate light much more effectively than larger particles (Baker and Lavelle, 1984). This scattering characteristic was not an issue as the proposed system uses several different exposures to find the optimal contrast to maximise the dynamic range of light intensity shown in Figure 2(b). The results were found to scale linearly with exposure, provided the images were not saturated or under-exposed, thus 16 ms and 2.7 ms exposure times were chosen for the municipal and synthetic dairy based effluents respectively. This decision was based on maximising the dynamic range of light intensity shown in Figure 2(b).

Municipal Wastewater Effluent

For each municipal wastewater effluent sample, multiple images were taken, yielding 3 CET values. The CET measurements for each municipal wastewater effluent image are presented in Figures 5.1-5.3.

A strong linear correlation (Pearson's R) does not always indicate agreement between two datasets; therefore Lin's Concordance Correlation Coefficient (CCC) was also computed, it being a measure of agreement for variables with continuous data that compares the distance between the line of best fit of the datasets (Lin, 1989). In the water treatment area, previous studies have stated that a value for CCC above 0.9 is acceptable (McBride, 2005). However, the required level of agreement is subjective.

The mean and standard deviation of results shown in Figure 6(a) highlight the potential inaccuracy of some of the CETs. A small number of standard deviation values of 20 FAU or more were present. These higher standard deviations tended to occur for lower turbidity values <30 FAU. The municipal effluent CET results, shown in Figure 6(b), were examined against the spectrophotometer results and a high level of correlation was found with a Pearson's $R=0.9$ and Lin's $CCC = 0.86$.

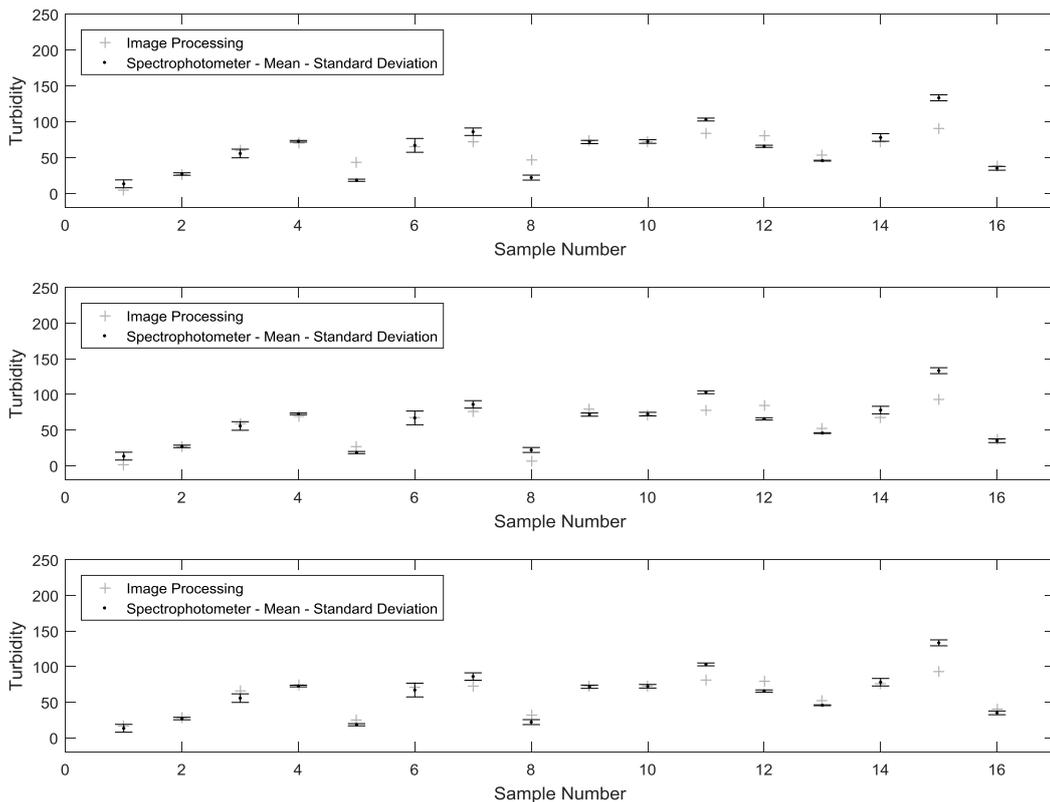


Figure 5. Individual image processing based turbidity measurements against spectrophotometer-based measurement, including standard deviation, for municipal wastewater effluent.

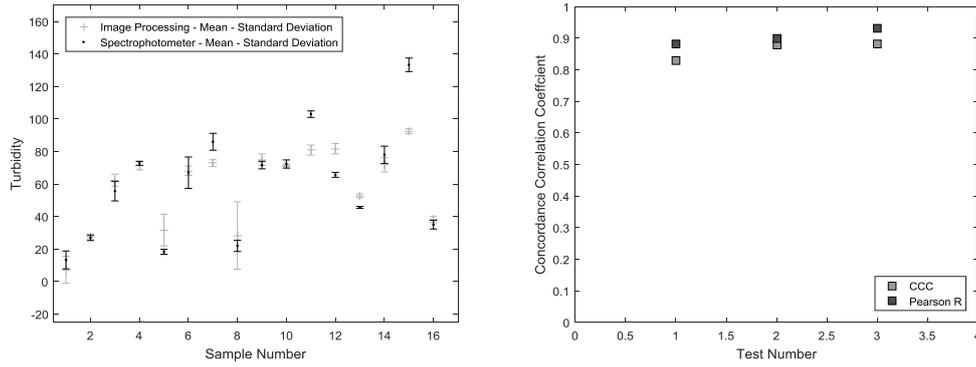


Figure 6(a). Comparison of mean and standard deviation of results for municipal wastewater effluent. Figure 6(b). Correlation coefficients for the 3 CET measurements of municipal wastewater effluent.

Synthetic Dairy-based Effluent

The second dataset of synthetic dairy-based effluent yielded similar results to the municipal wastewater effluent tests as shown in Figure 7. Figure 8(b) shows that a similar result was found with Pearson’s $R=0.9$ and Lin’s $CCC = 0.89$. The standard deviation of this dataset, shown in Figure 8(a), averages to 12 FAU. Two of the samples (9 and 15), are the primary contributors to this standard deviation value. These samples have a low turbidity and were both under and over-estimated, these were found to cancel out over the three CET values. This behaviour was also seen in spectrophotometer measurements. Without these samples, the standard deviation is 8 FAU.

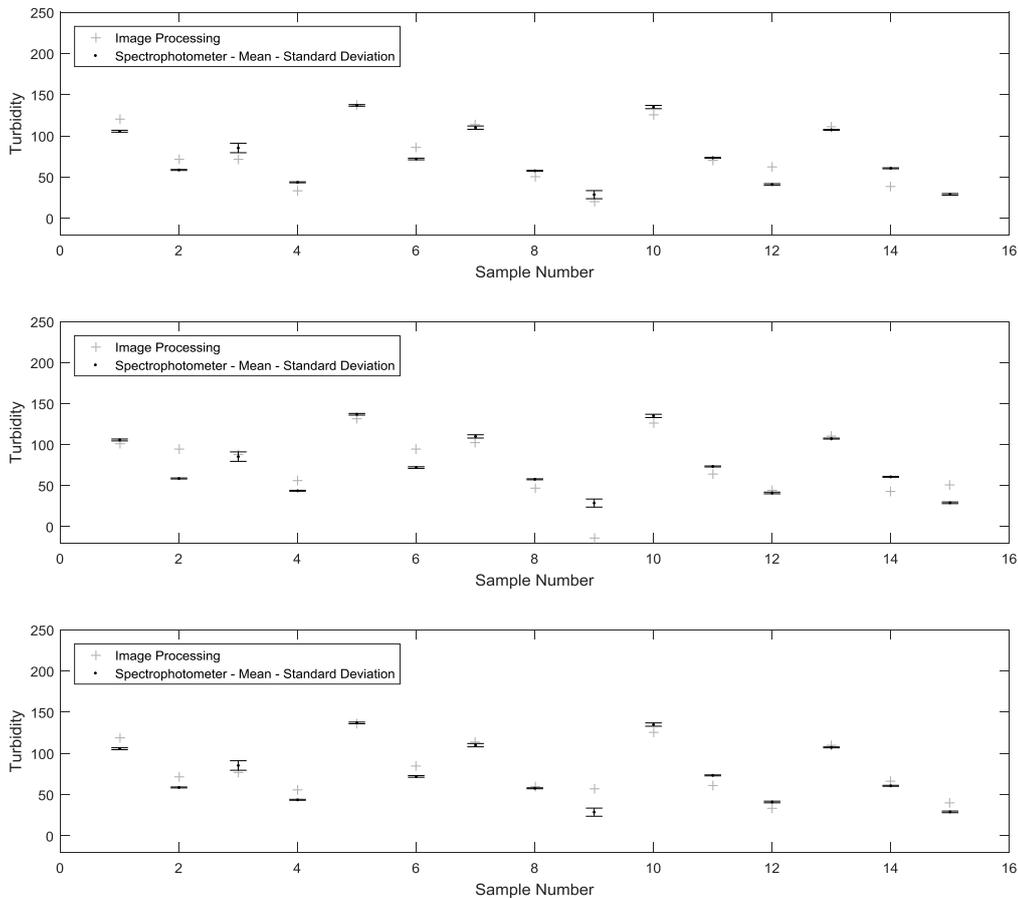


Figure 7. Individual image processing derived turbidity measurements compared with spectrophotometer-based measurement, including standard deviation, for synthetic dairy wastewater effluent.

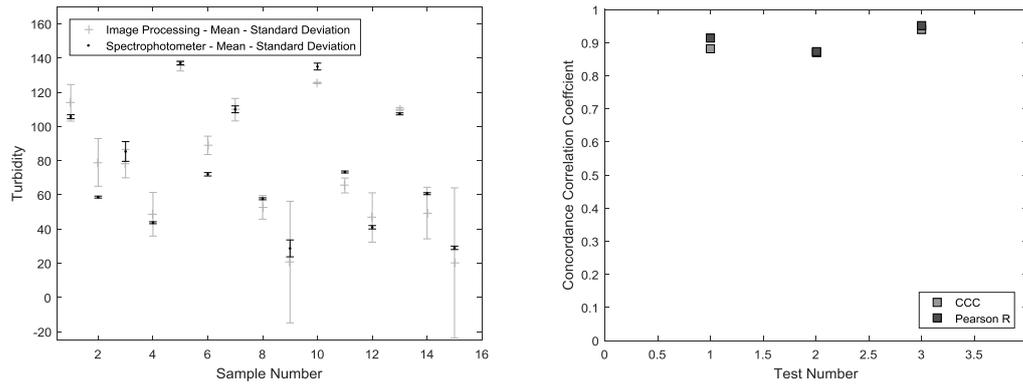


Figure 8(a). Comparison of mean and standard deviation of results for synthetic dairy wastewater effluent for full dataset.

Figure 8(b). Correlation coefficients for the 3 CET measurements for full dataset of synthetic dairy wastewater effluent.

Table 2. Summary of correlation results for CET and Spectrophotometer.

Dataset	Size	Pearson R	p-value	Lin's CCC
Municipal Effluent	16	0.9	<0.001	0.86
Synthetic Dairy Effluent	15	0.9	<0.001	0.89

Table 2 summarises the results from this study. A clear correlation between CET and the spectrophotometer can be seen for the two datasets examined. The p-values suggest all the results are statistically significant. There was still potential for a few outliers to be present in both datasets. However, these were instantaneous measurements approximating turbidity from a small volume of the effluent sample. The full volume imaged may not have been entirely homogeneous. The use of repeated measurements over time should help reduce this error. Also, as mentioned previously, the spectrophotometer can have an error of 10% or more and is a one-point measurement. An imaging system has the advantage of being able to apply a multipoint analysis to the measurement, three successive CET values were taken from a much larger effluent volume (spectrophotometer uses 20 ml samples, imaging system uses 2 L samples). In a commercial system examining the turbidity of an WWTP effluent stream, an operational decision would generally not be made based on one poor measurement. The trend would be monitored over time and appropriate measures taken after a series of tests confirm a degradation in performance. Implementing such a system would be beneficial for small to medium-scale WWTPs without regular maintenance staff, as well as large scale plants for out of hours monitoring. It could provide an early detection system for poor performance in the treatment process and keep a record of the effluent turbidity history for study. The inclusion of image recording allows the plant operator to visually examine the sample for an additional level of validation of the results.

Conclusions

In this paper, a new method of estimating turbidity using image processing is proposed. Replacing the manual procedure with an objective system based on image processing

provides both objectiveness and repeatability. By reducing the requirement for human intervention, the cost of monitoring can also be reduced.

Test results have shown that it is possible to relate the diffusion of light by a turbid fluid to the turbidity of that fluid. Control tests were used to determine the accuracy of the proposed system. The spectrophotometer error was found to be up to 10 %; though using repeated measurements can minimise this error. There was a clear correlation between the two turbidity measurement methods (spectrophotometer and CET) for the two datasets examined. The proposed system also has the advantage of being easily repeatable.

The proposed system could provide a simple one-dimensional performance metric that could be remotely monitored, even at WWTP locations where there is irregular maintenance or operators on-site. The data recording and analysis could be done on-site with relatively low-end hardware. A threshold value could be defined for a turbidity level, above which a notification could be sent to alert the plant caretaker that there is an issue with the treatment system. In areas where there is better connectivity, more detailed data could be sent from the plant, this would allow for more regular monitoring, and the images saved for record keeping purposes or further analysis.

Implementing such a system would lead to a reduction in manpower requirements, improve wastewater monitoring frequency, which is increasingly important, to meet more stringent discharge regulations and potentially as a result of this, reduce energy usage and increase WWTP efficiency.

While calibration was required for the system to produce a comparable turbidity value (in FAU), the CET value expressed in pixels is still a turbidity measurement and can be used as a metric itself. However, it is limited to the size of the vessel used, in this study with a 4 L vessel, the range of measured CET values in pixels was 400-900 pixels for a range of 0-250 FAU.

Future Work

Further development is needed for the ancillary systems to deal with loading, flushing and automatic cleaning of the vessel to ensure that calibration can be maintained over a long deployment. One potential implementation would be a flow cell with a purge and rinse cycle to avoid vessel fouling over time. Such a system could be valuable in monitoring and control of WWTPs, especially remote sites, where monitoring is infrequent.

There was a minimum level of turbidity this system can measure, fluids with low turbidity values (<15 FAU) contained insufficient particles to scatter any measurable quantity of light towards the image sensor. Perhaps a different light source with higher intensity could resolve this issue, or an imaging sensor with longer exposures times than used in this study.

There are two key areas for improvement of the current algorithm: (i) There is a potential for erroneous measurements due to spikes in the intensity profile as shown in Figure 3. (ii) The results showed a higher standard deviation of the CET measurements for turbidity values <30 FAU. A classification system is required to define what images/CET values are outliers and remove them from the calculation.

Firstly, increasing the number of images taken would yield more points of analysis. A CET could be classed as an outlier by manually examining the ROI of the image or the intensity across the image. To automate this, a classifier could be trained to disregard measurements where an incorrect value of exponential constant was chosen based on an aberration in the

profile, potentially due to a bubble or large flocculate in the ROI, or an excessively noisy intensity profile. This process could be included in the algorithm in a number of ways. Image processing techniques could be utilised to identify large flocs or bubbles in the ROI and remove the results from the CET calculation. Potential solutions would include a particle analysis that bins the image based on a intensity threshold and then disregards an image that contains multiple large flocs or bubbles. Alternatively, multiple intensity profiles could be examined for discontinuities and their level of agreement computed, from this the mode of the CET measurements could be selected and the rest of the results removed from the calculation.

The primary advantage of the proposed method is the potential for autonomous operation, though further work is required to implement such a system. The core technology proposed in this paper would form the basis for such a system.

Acknowledgements

The authors would like to acknowledge the funding from the European Union's Horizon 2020 programme under grant number 689817 (INNOQUA), the Enterprise Ireland Commercialisation Fund (Grant Number: CF2332) and the College of Engineering and Informatics PhD scholarship.

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