Design of an Embedded based Control System for efficient sorting of Waste Plastics using Near Infrared Spectroscopy

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Abstract - In this paper we present an embedded system solution to automate the sorting of different types of plastic by using the concepts of Near Infrared Spectroscopy (NIRS). Plastics are everyday used non-biodegradable materials when not disposed properly has adverse effects on the environment. For recycling of plastics different types of plastics (polymers) have to be identified and segregated. For economic reasons plastics must be identified and sorted instantaneously. The NIRS technique has been used for the instantaneous identification of plastics. Measurements made by NIRS are quite accurate and fast. To realize the above, a low cost Raspberry Pi based Control System, for efficient sorting of waste plastics has been developed. The necessary software required to interface the spectrometer with the Raspberry Pi as well as to process the NIRS data to obtain information on the polymer category have been written on the general-purpose, high-level programming language Python.

I. INTRODUCTION

A. *Background*

Plastics are organic polymers made from synthetic or semi-synthetic materials that can be molded and reshaped under pressure or heat. Plastics because of its attractive properties like durability, low cost and ease of manufacture has found its application over range of products from bottles, packaging, carry-bags to special items like aerospace moldings and oil pipelines.

Most of the disposed plastics are incinerated or end up as landfills. Plastics because of its durability, offer resistance to natural degradation and degrade slowly. Disposing them in the open has adverse effects on environment [2]-[3]. Degradation of plastics in landfills results in methane emissions, toxic sludge from plastic pollutants seep into soil & water and threaten the health and safety of humans & wildlife [4]. Plastic debris in oceans is known to be the cause of deaths various marine animals and birds, either because they become entangled or mistake it for prey and eat it. Recycling of plastics is therefore vital [5].

B. *Importance of Plastic sorting*

Only a small percentage of the plastic that are disposed is recycled. This is so because plastics which are contaminated with other plastics are not reusable. Plastics are polymers made up of petrochemicals and there exist different types of plastic with different chemical substances. While recycling plastics can be contaminated by the mixing of types and by non-plastic materials [5].

Segregating non-plastics, and different types of plastic like Poly Ethylene Teraphthalate (PET), High Density Poly Ethylene (HDPE), Poly Vinyl Chloride (PVC), Low Density Poly Ethylene (LDPE), Poly Styrene (PS) and Poly Propylene (PP) from each other are labor-intensive and hitherto, not many feasible techniques exist. Society of Plastic Industries (SPI) has standardized seven codes to identify different types of plastic for recycling. Widespread use of fillers and additives in plastics make them difficult to recycle because of the difficulty to remove fillers and additives from plastics. Additives are less widely used in PET (bottles, containers) & HDPE (milk jugs, shopping bags & shampoo bottle) when compared to other plastics. Due to the ease of recycling most of the recycled plastics is PET & HDPE. The need of the hour is affordable and efficient method that can sort different plastics quickly and accurately.

C. *Near-InfraRed Spectroscopy and Multivariate analysis as potent tools for classification of plastics*

Near-infrared spectroscopy (NIRS) [8]-[10] is a spectroscopic method that uses the near-infrared region of the electromagnetic spectrum (from about 780 nm to 2500 nm). NIRS is very useful in probing bulk material with little or no sample preparation. Due the above reasons NIRS has been widely applied in diverse fields from agricultural, petrochemical, pharmaceutical, clinical diagnostics, environmental and even characterization of plastics [7]-[10]. Near-infrared spectroscopy is based on molecular overtone and combination vibrations caused by stretching and bending. The molecular overtone and combination bands seen in the NIR region are typically very broad and lead to complex spectra. Therefore, it can be difficult to assign specific features to specific chemical components. For this reason, multivariate calibration techniques [7] are often employed to extract the desired chemical information. Examples of such methods include Spectral Angle mapping (SAM), Principal Components Analysis (PCA), Partial Least Squares (PLS), or Artificial Neural Networks (ANN). Careful selection of a set of samples representative of whole population and application of multivariate calibration techniques is essential for near-infrared analytical methods.

D. *Theme of paper – NIRS based automatic plastic sorting with computational algorithms on Raspberry Pi*

In this paper we present our work towards the development of a low cost, Raspberry Pi based control system for the sorting of different plastics through Near InfraRed Spectroscopy (NIRS). The general-purpose, high-level programming language Python has been used to interface the NIRS spectrometer and other instrumentation peripherals with the embedded board as well as to implement the multivariate analysis algorithms.

II. Near InfraRed Spectroscopy and Multivariate Analysis for Identification of Plastics

A. *Near-infrared Spectroscopy*

In the NIR region absorption bands correspond mainly to overtones and combinations of fundamental frequencies. The vibration of molecules can be described using the harmonic oscillator model, by which the energy E_{vib} of the different, equally spaced levels can be calculated from [10],

$$E_{vib} = (v + \frac{1}{2})\frac{h}{2\pi}\sqrt{\frac{k}{\mu}} \quad (1)$$

where, v is the vibrational quantum number, h is Planck's constant, k is force constant and u is reduced mass. Transitions take place between consecutive energy levels that cause change in the dipole moment. However, the harmonic oscillator model fails to explain behavior of actual molecules, as they don't account for Columbic repulsion between atoms or dissociation of bonds. As a result, they more closely represent anharmonic oscillations with unequally spaced energy levels, given as [10]:

$$\Delta E_{vib} = hv[1 - (2v + \Delta v + 1)y] \quad (2)$$

Here y is the anharmonicity factor. The anharmonicity can result in transitions between vibrational energy. These transitions between non-contiguous vibrational states yield absorption bands known as overtones (first and second overtone, respectively) at, approximately, multiples of the fundamental vibrational frequency. Also, they are much less likely than the fundamental transitions, so the bands are much weaker (the band for the first overtone is 10–100 times weaker than that for the fundamental frequency, depending on the particular bond). These bands appear between 780 nm and 2000 nm, depending on the overtone order and the bond nature and strength. In polyatomic molecules, two or more vibrational modes can interact in such a way as to cause simultaneous energy changes and give rise to absorption bands called combination bands, the frequencies of which are the sums of multiples of each interacting frequency. NIR combination bands appear between 1900 nm and 2500 nm.

The intensity of NIR bands depends on the change in dipole moment and the an-harmonicity of the bond. Because the hydrogen atom is the lightest, and therefore exhibits the largest vibrations and the greatest deviations from harmonic behavior, the main bands typically observed in the NIR region correspond to bonds containing this and other light atoms (namely C–H, N–H, O–H and S–H); by contrast, the bands or bonds such as C=O, C–C and C–Cl are much weaker or even absent.

B. *Why NIRS for plastic identification*

NIR absorption or reflectance spectroscopy is very fast and well suited to analyzing transparent or lightly colored polymers [8]. NIR spectra of common polymers found in the post-consumer and post-industrial waste stream are quite distinct. For this reason it is ideal for plastic identification and sorting. NIR spectroscopy offers many advantages for sorting waste plastics. It enables rapid reliable identification (within milliseconds) and is sufficiently robust to operate in dirty and vibration-prone industrial environments which are typical of sorting facilities.

The absorption of light in the NIR spectral range (14300 – 4000 cm^{-1}) is due to overtone or combination vibrations of polymer molecules. This can be an advantage since the reduced absorbance in the NIR allows the registration of spectra of bulky, high path length samples such as plastic bottles, which are of practical interest in many post-consumer-recycling processes. The C – H, O – H, N-H and S–H bands observed in NIR spectra can be characteristically attributed to specific polymers, thus enabling identification of most commonly used plastics. For example, the NIR spectra of HDPE exhibit a peak at around 1200 nm, which is, not present in PET and is only small for PVC. PET on the other hand exhibits three characteristic peaks in the region 1400 –1700 nm (refer Fig. 1).

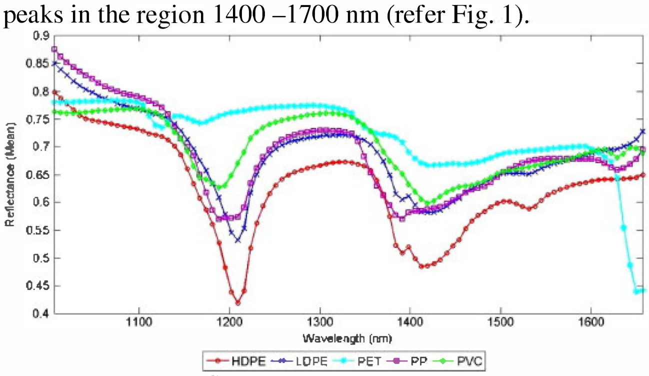

Fig.1: NIRS spectra of different plastic classes.

A further advantage of NIR is that the NIR photo detectors namely, germanium, indium arsenide, or indium gallium arsenide, have short response times and high detector sensitivities. Also, quartz fiber optics with low attenuation and low cost can be used for convenience and for remote sensing. NIR spectrometers typically have no moving parts and therefore they are not affected by the vibration or dust/dirt typical of plastic recovery facilities. Furthermore, NIR instruments require little maintenance and provide excellent reproducibility with negligible instrumental drift [8]-[10].

C. *Multivariate Analysis as a vital cog in NIRS analysis*

Multivariate Analysis (MVA) [7] is the science of relating measurements made on a chemical system to the state of the system via application of mathematical or statistical methods and of designing optimal experiments for investigating chemical systems/ specimen. The goal of many MVA techniques is an efficient production of an empirical or semi-empirical model, derived for data, which is used to estimate one or more properties. Apart from obtaining a model that provides useful predictions, MVA techniques can also be used to obtain insight about a chemical system.

D. *From NIRS to information on plastic class*

While the NIRS contains valuable clues to the nature of the polymer, it has to be accompanied by MVA to unravel information. The data pretreatment and MVA methodology employed to evaluate the plastic polymers are listed below:

- Outlier detection: Outliers are aberrations in the data which occur due to errors in the instruments or in the acquisition of data. Outliers can significantly alter the characteristics of the data and hence have to be removed. In this work we employ Principal component analysis (PCA) [11] to identify and remove the outliers.
- Baseline correction: Baseline correction is the process of removing background noise in the measurement of the data. In this work we have used the Savitzky Golay (11 point, 1st order differentiation) [12] technique to correct the statistical noise in the spectral data.
- Scatter Correction: Scatter correction is necessary to offset any variations in the measurements due to differences in particle sizes (for powdery samples), effective path length and light scattering. In this effort we use the popular multiplicative-scatter correction (MSC) [13] technique to correct for artifacts related to scattering.
- Pattern recognition, validation and analysis: To build the model and validate it we have applied the Successive Approximation Method (SAM) [14].

E. *Spectral Angle Mapping (SAM)for Pattern recognition*

The spectral Angle Mapping is a simple algorithm for pattern correlation and recognition which does not involve complex statistical evaluation. It is commonly used for directly comparing a given spectra to a known spectra (usually determined in a lab or in the field with a spectrometer). This method uses all the features supplied to it to classify an unknown plastic polymer based on its NIRS spectrum. The spectral data (known as well as unknown) are considered as vectors in a multi-dimensional space and the angle between the vectors is used to determine their relative correlation. Taking dot product of the two spectrums does the projection and finding the angle between them.

Consider that two spectrum A and B, represented by vectors **a** and **b**, are under investigation. The two spectrum are compared by obtaining the angle of inclination between them using the formula,

$$\theta_{\mathrm{SAM}} = \cos^{-1}\left(\frac{a \bullet b}{\| a \| \, \| b \|}\right), \qquad (3)$$

where, the operator $\bullet$ stands for the dot product of the vectors and the operator $\| \; \|$ connotes the Frobenius norm. The classification is based on finding the minimum or smallest angle between the unknown spectrum and the polymer class reference (library) spectrum. The cosine of the distance between these two vectors gives the correlation between their respective spectra. The above process is followed for all the available reference signatures. The reference signatures also include that of blank capture (i.e., without any material placed) to recheck for material availability.

III. Computational Hardware and Software

The MVA algorithms presented above were implemented in Python language and ported onto Raspberry Pi boards.

A. *Raspberry Pi*

Raspberry Pi [15]-[16] is an open-source single-board microcontroller. The hardware consists of a simple open hardware design for the Raspberry Pi board and on-board input/output support. The software consists of a standard programming language compiler and the boot loader that runs on the board. Raspberry Pi hardware uses Linux kernel-based operating system [15]-[16].

Raspberry Pi can receive inputs from a variety of sensors and can control its environment by controlling Halogen lights, motors, Air nozzle and other actuators. The Raspberry Pi board is programmed using the Python programming language.

B. *Python*

Python [15] is a general-purpose, high-level programming language and is famous for its code readability. Raspberry Pi extends excellent support to the Python language, some of the other merits of programming with Python in comparison to other mathematical tool/statistical packages such as MATLAB™ or R language. Python has a separate GPIO module which allow us to access GPIO pins on Raspberry Pi. Python supports multiple programming models, including object-oriented, imperative and functional programming styles. Python is a scripting language, but can also be used for non-scripting.

C. *Interfacing the embedded hardware and NIRS instrument*

Serial communication is used for communicating between Raspberry Pi boards and the NIR Spectrometer. Serial communication is the process of sending data one bit at a time, sequentially, over a communication channel or computer bus. An RS232 serial port operates at ±12V and can damage the Raspberry Pi board if connected directly to the pins of the Raspberry Pi. Hence, we use a RS-232 to USB converter that would directly go into the USB port of the Pi to interface the NIR spectrometer and the embedded system.

IV. Technical Description of the System

A. *Components of the System*

The schematic diagram of the plastic sorter is shown in Fig. 2. The system consists of the following units:

- a conveyor belt assembly for on-line capture of spectral signature of plastic materials that are to be sorted,
- a white light source (halogen lamp) with wide spectral response,

- an optical assembly to collect rays reflected by the plastic material,
- a NIR based Diode Array Spectrometer (DAS) which interprets the optical information and converts into digital data,
- proximity sensor
- an embedded system to collect digital data from the spectrometer and perform necessary mathematical computations to identify nature of polymer,
- an Air-Jet nozzle which is used to segregate the material of choice.

B. *System Operation*

The process flow diagram is depicted in Fig. 3. The operation of the system is briefly explained below:

1. The singulated consumer/domestic waste polymer samples move on a fixed speed conveyor.
2. The samples are irradiated by ordinary lamps of 250 watts.
3. Optical device senses the vicinity of samples and initiates the DAS to capture the signal.
4. The optical assembly collects the reflectance light and through a multi-mode optical fiber communicates it to the DAS.
5. The embedded system collects the spectrometer data performs baseline correction, scatter correction and pattern recognition of the signature of the polymer and uses decision supporting system for classification.
6. Jet Nozzles are activated based on the command signal to eject classified plastics into their respective bins.
7. The data base is updated for all the classified consumer polymers.

C. *Graphical User Interface*

In order to control and configure the plastic sorter a graphical user interface (GUI) has been developed. The GUI is based on python based GUI tool tkinter. Fig. 4 shows two snapshots of the GUI taken before and during the sorting of plastics.

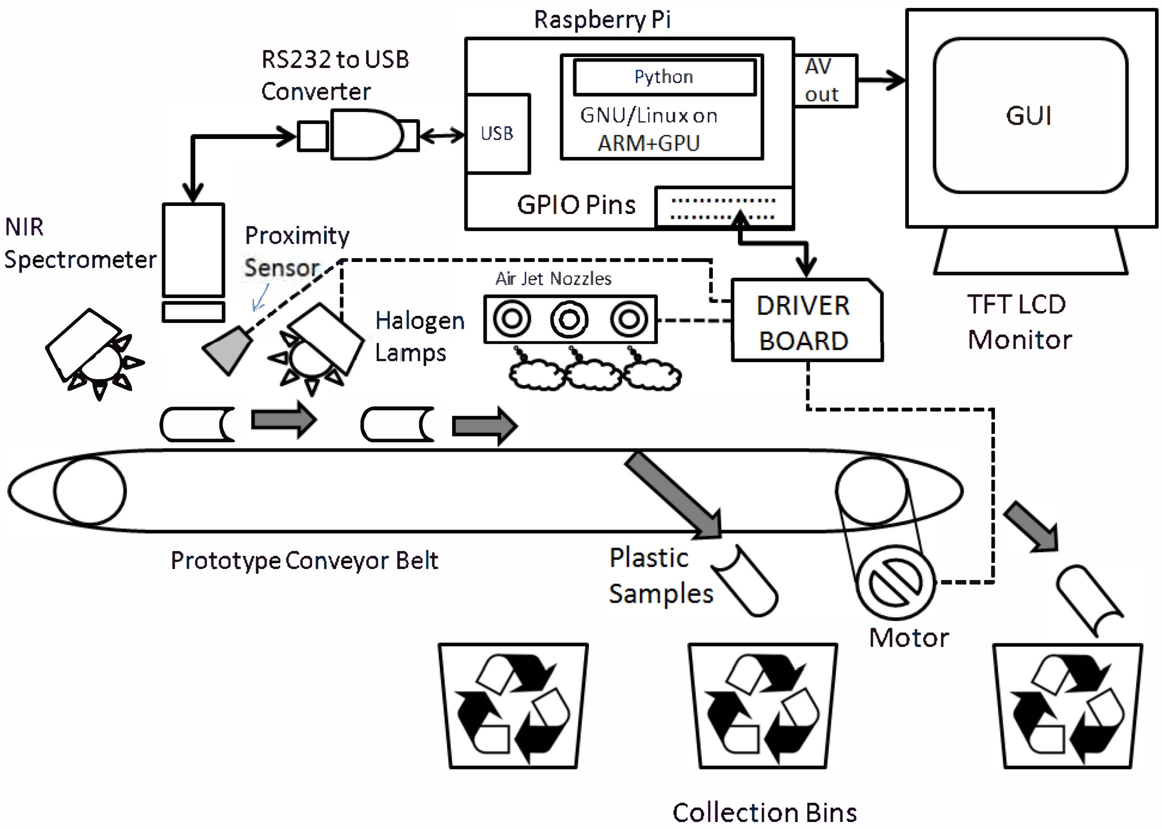

Fig. 2: Architecture of the complete system.

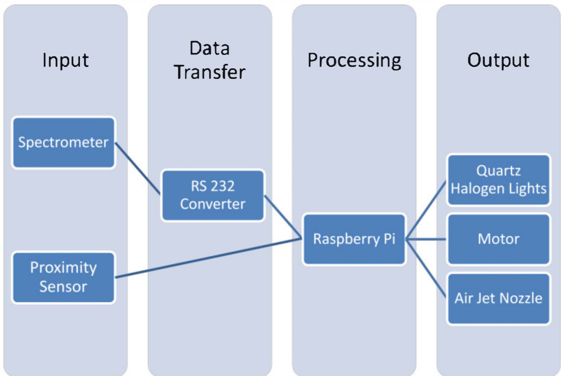

Fig. 3: Process Flow Diagram.

(a) Before start of sorter

(b) During the sorting of plastics

Fig. 4: GUI for plastic sorter.

V. Comparison with earlier Arduino system

The system was earlier ported onto an Arduino processor [17]. In relation to the Arduino based system, the Raspberry Pi system offers many advantages. By using a Raspberry PI, this project would make the existing plastic sorting embedded system more effective. The existing plastic sorting system runs on Arduino Microcontroller board based on C language. The Pi has a clear advantage for complex networked and high performance embedded applications, and those which involve driving a video display or USB peripherals.

The Raspberry Pi board runs Python, which is simpler and more user friendly due to its inbuilt libraries and related functions and it is more effective and gives accurate results. As the Pi runs on a LINUX environment interfacing new devices becomes much simpler compared to Arduino interfacing. The Arduino employs an 8-bit ATmega series microcontroller whereas the Raspberry Pi is based around a 32-bit ARM processor, and the Arduino is typically clocked at between 8-16MHz and with 2-8kB of RAM available, and in contrast the Raspberry Pi can be clocked at up to 1GHz and may have up to 512MB of RAM. On top of which the Pi has a GPU and video outputs, Ethernet as standard and USB host ports. The Pi has a clear advantage for complex networked and high performance embedded applications, and those which involve driving a video display or USB peripherals .This kind of efficiency the system can have a great impact on plastic recycling.

VI. Results and Discussions

A. *Description of sample set*

A batch of 184 samples of 5 major plastic varieties was considered, the details of which are described in Table I. Each batch contained coloured and transparent plastics.

TABLE I: Description of sample set

	PET	HDPE	PS	PP	PVC	Total
Size of Sample set	54	29	33	37	31	184

B. *Data treatment and Spectral Analysis*

The collected samples were analyzed using a 128 pixel resolution Microparts STEAG NIR instrument with spectral range of 1000 nm to 1700 nm. The obtained spectra were pretreated for background, thermal and optical noise using the signal processing techniques described in Section II-D. The treated data was then analysed using Principal Component Analysis (PCA) to identify and remove outliers in the samples. During pattern recognition samples which covered boundary conditions was used as reference.

C. *Classification of plastics using Spectral Angle Mapping*

Table II shows the comparison of correlation between different plastic items. The tabulated values were obtained by calculating $\cos(\theta_{SAM})$ of the angle subtended by the two vectors studied. A value close to 1.00 implies close match while a value close to 0 corresponds to poor correlation.

The best match is declared to be the one for which $\cos(\theta_{SAM})$ is maximum (or alternatively, the θ_{SAM} is close to 0). To make the comparison to be effective the calibration model is formed with average spectrum of the individual class spectra hence the number of comparison can be greatly reduced. The class of plastic is then published on the GUI and necessary actuators are activated to sort the plastic in their respective bins.

TABLE II : Tabulated values of $\cos(\theta_{SAM})$ for plastic classes.

	PET	HDPE	PS	PP	PVC
PET	**0.993348**	0.687779	0.607282	0.660003	0.535888
HDPE	0.701992	**0.997355**	0.703522	0.8418	0.656706
PS	0.795542	0.645026	**0.983352**	0.646704	0.552696
PP	0.758015	0.636601	0.742697	**0.977152**	0.699741
PVC	0.573234	0.694659	0.53697	0.77783	**0.989361**

D. *System performance evaluation*

The system has undergone rigorous trials to check for its accuracy and robustness. Regular tests have been conducted to ascertain its repeatability and consistency of performance. Table III provides a statistical data of the results obtained over a period of 1 week.

TABLE III: Tabulation of classification performances

Sample type	Number of trials	PET	HDPE	PS	PP	PVC
PET	452	452	0	0	0	0
HDPE	381	0	381	0	0	0
PS	366	0	0	366	0	0
PP	411	0	0	0	411	0
PVC	347	0	0	0	15	332

E. *Key performance features*

Some of the key features and advantages of the developed system are listed below,

1. Automated, low cost device which can sort five groups of polymers through pattern recognition.
2. Smart and fast system capable of sorting up to 80 plastic items per minute.
3. System can handle bulk input (target specification is 4 tonnes of plastic per day).
4. Classification of plastics done to a high degree of accuracy. For PET, HDPE and PS materials the accuracy is close to 100% while PP and PVC the accuracy is around 95 %.

VI. Conclusions And Future Research Topics

In this paper we presented our work on developing an affordable and efficient system that can sort different categories of plastics quickly and accurately through non-destructive method for efficient recycling. The robust and indigenously integrated system is capable of handling the vagaries of environmental conditions.

The system employs the concepts of NIR spectroscopy & multivariate analysis and has been designed and implemented using Raspberry Pi system. The computational algorithms and GUI were developed using Python.

The plastic sorter system can differentiate among 5 types of plastics, i.e. PET, HDPE, PVC, PS and PP. Not only is the system robust, it is also accurate (near 100% accuracy for PET, PS and HDPE and near 95% accuracy for PVC and PP), can handle vast quantities of plastic (about 4 tonnes of plastic per instrument per day) and sort them quickly (up to 80 plastic items per minute). It is worth mentioning here that the accuracy of results obtained match with the requirements of the plastic waste management industry.

The system developed by the authors offers great scope for further improvement, for instance, the speed of operation. The diode array NIR spectrometer currently used takes about 580 milliseconds (ms) for reading the data per scan while the time taken for the execution of computational algorithms is 20 ms. State-of-art NIRS devices currently available come with high-speed USB interfaces which take as less as 1 ms to acquire the spectral data. These fast and accurate NIRS devices can be employed to significantly increase the speed of operation of the system. Further, the accuracy of the results (particularly for the sorting of PVC and PP items) can be improved by adding more reference samples to the pattern recognition algorithm. However, a penalty may have to be paid in terms of the execution time.

Acknowledgement

The authors express their heartfelt gratitude to Dr. A.S.V Sarma, Scientist-in-Charge, Mr. R. Sridhar, Chief Scientist and Mr. V. Venkatakraman, Senior Principal Scientist (Retd.), of CSIR-CEERI, Chennai, for their guidance, constant motivation and support.

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