Automated Data Mining of the Single Objects From Blurred Astronomical CCD Frames Using the Lucy-Richardson Deconvolution

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Abstract

In this paper, we detail the development and application of an innovative method for automated data mining of single objects within blurred astronomical CCD images, employing the Lucy-Richardson deconvolution algorithm for enhanced image restoration. The extraction of precise data from images affected by various distortions, including atmospheric interference and instrumental limitations, presents a substantial challenge in the field of astronomy. Our research presents a web-based application framework integrating FastAPI, React, Python RQ, and PostgreSQL, designed to facilitate the uploading of blurred images by astronomers and deliver deconvolved, high-resolution images. The implementation of the Lucy-Richardson deconvolution algorithm is central to our approach, offering a robust solution for the reduction of image blur and the recovery of fine details within celestial observations. This paper discusses the asynchronous processing capabilities enabled by Python RQ, allowing for the efficient management of the computationally demanding deconvolution process, and details the role of React in providing a dynamic user interface for interactive data submission and retrieval. Furthermore, we explore the utilization of PostgreSQL for the secure and efficient storage of user data and processed images. Our findings demonstrate significant improvements in image quality and object discernibility, facilitating a deeper analysis of astronomical data. This paper underscores the potential of combining advanced image processing techniques with modern web technology to enhance the field of astronomical research, offering a powerful tool for the accurate identification and analysis of celestial bodies in blurred CCD frames. The contributions of this work extend beyond technical implementation, highlighting the implications for future research and the potential for new discoveries in the space.

Keywords

Data mining, data cleaning, image processing, object detection, recognition patterns, tracking, Lucy–Richardson deconvolution, series of images, CCD frames, blurred frames, database, Python, Docker, Redis

1. Introduction

The advent of digital imaging in astronomy has revolutionized our capacity to observe and analyze the cosmos, enabling the capture of celestial phenomena with unprecedented detail. However, this technological advancement brings with it a significant challenge: the degradation of image quality due to various factors, including atmospheric turbulence, optical system imperfections, and the inherent limitations of Charge-Coupled Device (CCD) cameras [1].

These distortions result in blurred images that obscure the fine details of astronomical objects, significantly hindering scientific analysis and discovery.

One of the main factors affecting image quality is the level of noise. When imaging faint objects, even a small amount of noise on the camera sensor can significantly distort the image and hinder its interpretation. Despite significant improvements in noise reduction in modern cameras, this aspect remains a problem when dealing with very faint and distant objects [2].

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Another important factor is atmospheric conditions. Atmospheric turbulence and atmospheric distortions can significantly affect the quality of images and its typical shape or form [3], especially when working with high magnifications.

There are following sources of image quality degradation (the list is not full) [4]:

- atmospheric disturbance;
- diffraction effects;
- loss of diurnal tracking;
- inaccuracies in satellite tracking;
- wind gusts.

Examples of blurry images of objects in digital frames are shown in the Figure 1.

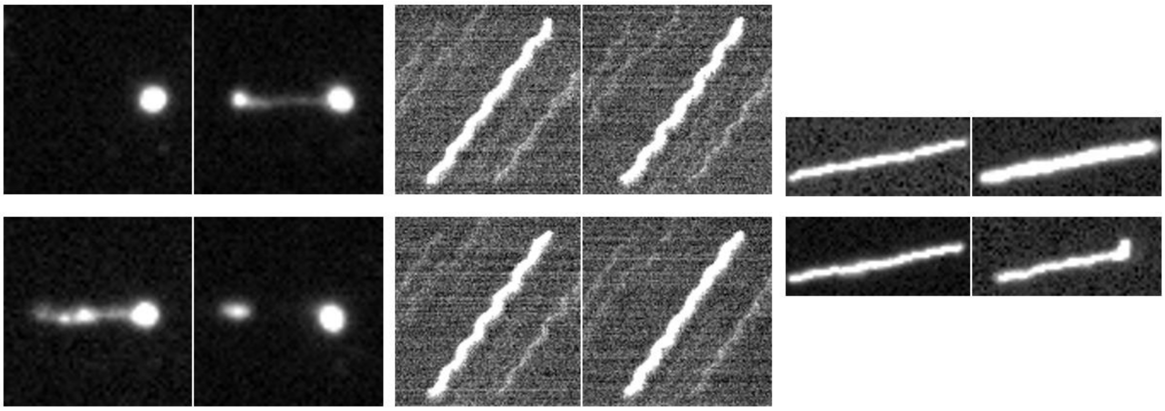


Figure 1: The examples of blurry images of objects in digital frames

The problem is twofold. Firstly, the blurring of images leads to a loss of critical data, which is essential for the accurate identification and characterization of celestial bodies [5]. This limitation impacts a wide range of astronomical studies, from the tracking of near-Earth objects [6] to the exploration of distant galaxies, affecting both the quality and reliability of research findings. Secondly, the manual restoration and analysis of these images are time-consuming and labor-intensive, requiring significant expertise and computational resources.

The necessity to solve this problem arises from the crucial role of high-quality astronomical images in advancing our understanding of the universe. Enhanced image clarity can reveal previously unseen features, enabling more accurate measurements and facilitating deeper insights into the composition, behavior, and evolution of astronomical objects.

Moreover, the automation of image restoration and data mining [7] processes can greatly accelerate research efforts, making it possible to analyze larger datasets with improved efficiency and statistical precision [8].

In this context, the application of the Lucy-Richardson deconvolution algorithm [9] offers a promising solution. By iteratively refining the estimation of the true image, this algorithm can significantly reduce blurring, thereby restoring the detailed structure of celestial objects.

The development of a web-based platform that integrates this algorithm with modern web technologies and databases further democratizes access to advanced image processing tools, empowering astronomers to conduct their research with greater speed and accuracy using the astronomical catalogs [10] and big data [11] received from the different telescopes or even from the Virtual Observatories [12].

This paper seeks to address the pressing need for an efficient and accessible method of extracting clear, detailed data from blurred astronomical images. By automating the process of image restoration and data mining [13] through a user-friendly web application, we aim to enhance the scientific community's ability to conduct high-quality astronomical research, paving the way for new discoveries and advancements in our understanding of the universe [14].

2. Related Works

The uniformity of the standard form of the image of objects is an important factor influencing the subsequent process of the astronomical object identification with the data in astronomical catalogs [15]. Therefore, it is necessary to conduct an in-depth analysis of literature data to compare methods for preparing images for the identification process itself. Such methods are expected to reduce the blurring of images and shift in the positional coordinates of the frame center between the frames themselves in the series.

There are a lot of different causes of the image blurring: motion blur (it is related to the situation when the camera shake, subject movement, or any form of motion during image capture can lead to motion blur); incorrect focus settings or depth-of-field issues can result in defocus blur; optical aberrations (lens imperfections, chromatic aberrations, and other optical distortions can contribute to blurring); electronic noise in the image sensor can introduce a form of low-level blur.

And because of such image blurring the following common problems and impact on image quality can be observed:

- loss of details – blurring can lead to a loss of fine details and sharpness in the image, impacting overall visual quality;
- reduced information – blurred images may lack critical information for applications like medical diagnosis or surveillance;
- aesthetic issues – in photography and visual arts, unintentional blurring can affect the intended artistic expression.

There are few traditional deblurring techniques, which can be used for resolving the purpose of the research: convolutional methods (classical deblurring techniques, which use of convolutional operations to reverse the effects of blurring) or wiener filtering (statistical method for minimizing noise and recovering the original image).

For example, classical methods of computer vision [16] are not able to provide the required level of processing speed. These methods require the analysis of all pixels of potential objects to determine their typical shape. However, when the standard form is heterogeneous, objects are confused, which increases the processing and identification time. Methods for estimating image parameters [17] are based on the analysis of only those pixels that potentially belong to the object under study. Their disadvantage is the inability to determine specific pixels and reject those whose intensity exceeds a specified limit value initially accurately.

In the study [18], the authors use automatic selection of a reference point to select calibration frames. However, this is not a requirement for the identification process itself. Because if there are artifacts in the image, these control points may be false. Thus, the accuracy of identification with real objects from the astronomical catalog decreases. The works [19] propose segmentation method. However, it only work with single images of objects. That is, in the case of a variety of standard shapes (stroke, extended, circular), this method will not provide the necessary accuracy due to the ambiguity in the number of brightness peaks.

This variety of typical shapes also influences various methods of Wavelet transform [20] and time series analysis [21]. The disadvantage of these methods is that they can only work with "pure" measurements, so image heterogeneity will greatly spoil the overall indicator.

Another implementation is presented in the study [22] in the form of an additional calibration procedure to avoid the internal coma of the telescope's secondary mirror. But, to equalize brightness and remove "highlights", there is a brightness method that is more improved in accuracy and quality using an inverse median filter [23]. However, the disadvantage of these implementations is the poor accuracy of positional coordinate estimates during the process of identification between frames of the same series.

The matched filtering procedure is also known [24], but it uses only an analytical image model. The disadvantage of this procedure is the inaccuracy of identification when the typical image of an object is different in different frames of the series. The classical method of adding frames [25] to improve the “super” frame is also ineffective in the case when the SSO image does not have clear boundaries on all digital frames of the series.

But anyway, there are still a lot of challenges and limitations, like computational complexity (especially for the deep learning deblurring algorithms), generalization (to ensure the generalization of deblurring models across different types of blurs and diverse image content) or even blind deblurring issues when we try to recover the exact blur kernel without prior information.

So, addressing the common problem of blurred images involves a multidimensional approach, including traditional techniques and cutting-edge advancements in deep learning. The challenge lies in developing robust and efficient methods that can generalize well across various blur types and image content while meeting the specific requirements of different applications.

3. Methods

During the image deconvolution software development, we have architected a solution that seamlessly marries advanced mathematical algorithms with a user-friendly web interface. At the core of this software lies a mathematical module, designed to implement the Lucy-Richardson deconvolution algorithm for the precise restoration of blurred astronomical images [26]. This module serves as the foundation upon which our web application is built, allowing users to easily upload images for deconvolution and retrieve enhanced results.

3.1. Lucy–Richardson deconvolution

The Lucy-Richardson deconvolution algorithm is an iterative technique designed for the restoration of images that have been blurred by a known point spread function (PSF) [27].

The PSF describes how a point source of light (e.g., a distant star observed through a telescope) appears on an imaging system (like a CCD camera) due to the effects of the system's optics and other factors [28]. Instead of being captured as a single point, the light from the source spreads out, resulting in a blurred spot in the captured image. The shape and size of this spot are determined by the PSF, which is influenced by several factors:

- optical system: imperfections in the lenses, mirrors, and other components of the optical system can cause light to scatter, leading to a broader PSF.
- atmospheric conditions: for ground-based telescopes, variations in the atmosphere (e.g., turbulence) can distort the incoming light, affecting the PSF.
- instrumental factors: characteristics of the imaging sensor itself, including pixel size and shape, can influence the PSF.
- diffraction: the wave nature of light causes it to diffract around the edges of telescope apertures, contributing to the PSF's shape.

In image processing and deconvolution techniques, knowing the PSF allows for the correction or significant mitigation of these blurring effects, aiming to restore the image to its original, unblurred state.

Observed image can be expressed through a transition matrix p that acts on a base image [29]:

$$A_{out} = \sum_j p_{i,j} u_j, \tag{1}$$

where A_{out} – distorted image;
$p_{i,j}$ – element of transition matrix;
u_j – intensity of the original image pixel j.

In the context of the Lucy-Richardson deconvolution algorithm, the PSF is a critical input as it directly influences the deconvolution process. The algorithm uses the PSF to reverse the blurring effects by iteratively refining an estimate of the true image. The algorithm is particularly wellsuited for astronomical images, where the need to recover as much spatial information from distant celestial objects is paramount.

The essence of the Lucy-Richardson algorithm lies in its iterative approach [30] to estimate the original image by minimizing the difference between the observed image and an image convolved with the PSF. Mathematically, the process can be described by the following formula, which updates the estimate of the true image:

$$A_{deb}^{t+1} = A_{deb}^{t}\left(h_{PSF} \star \frac{A_{out}}{h_{PSF} \otimes A_{deb}^{t}}\right), \tag{2}$$

where A_{deb}^{t} – is restored image on the t iteration;
A_{out} – distorted image;
h_{PSF} – the flipped point spread function;
$\star$ – correlation operation;
$\otimes$ – convolution operation.

The algorithm begins with an initial guess for the true image, often the observed image itself or a uniform image. At each iteration, the algorithm refines this guess by applying the formula above, effectively sharpening the image by compensating for the known distortions introduced by the PSF. The iterative process continues until the algorithm converges to a stable solution, typically determined by a predefined number of iterations or when the improvement between iterations falls below a certain threshold.

One of the strengths of the Lucy-Richardson algorithm [31] is its ability to enhance images without amplifying noise significantly, a common challenge in image deconvolution. This property is particularly valuable in astronomy, where the signal-to-noise ratio in images can be low, and preserving the integrity of the data is crucial.

In applying the Lucy-Richardson deconvolution to astronomical images, researchers can reveal details that were previously obscured by blurring effects, enhancing the scientific value of the observations. This algorithm enables the extraction of finer spatial details from images of celestial objects, facilitating more accurate measurements and contributing to a deeper understanding of their physical properties and behaviors.

By integrating the Lucy-Richardson deconvolution into a web-based application, as described in this paper, we offer astronomers a practical and accessible tool for image restoration, significantly advancing the analytical capabilities available to the field.

3.2. Software architecture

The software was built using a tech stack that includes Python, React, FastAPI, Redis, Redis Queue, Docker, and Docker-compose, each serving distinct functions critical to the software's functionality. Overall image deconvolution software architecture is shown in a Figure 2 below.

Python's utilization stems from its rich ecosystem of libraries and ease of integration, allowing seamless integration of scientific algorithms and backend services [32]. React, is used as a robust JavaScript library, and empowers the creation of a dynamic and intuitive user interface, essential for enhancing user engagement and interaction with the software.

FastAPI plays a pivotal role in facilitating efficient communication between the frontend and backend components of the software, ensuring rapid response times and optimal performance. The integration of Redis and Redis Queue [33] is instrumental in managing session data, caching frequently accessed information, and handling asynchronous task queues, all of which contribute to the scalability and responsiveness of the software.

Docker and Docker-compose are employed to containerize the software and its dependencies, enabling consistency across different environments, and simplifying deployment processes [34]. This containerization approach ensures that the software can be seamlessly deployed and scaled across various platforms, enhancing its portability and maintainability.

At the core of the software lies the Lucy-Richardson deconvolution algorithm, which is called under Python to leverage its computational capabilities. Although the algorithm itself is not implemented using Python, Python serves as the interface through which the algorithm is invoked and utilized within the software. This integration enables the software to perform high-fidelity image deconvolution, enhancing the quality and accuracy of astronomical image analysis.

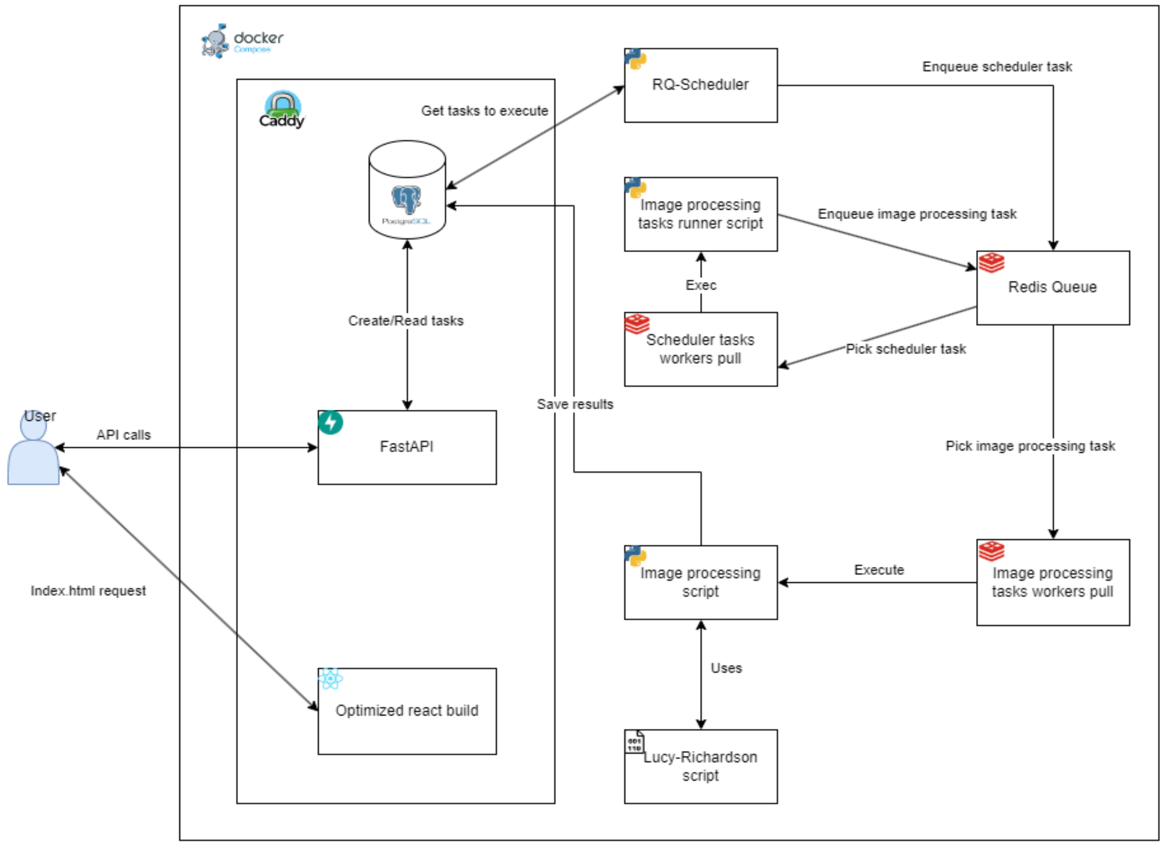


Figure 2: Image deconvolution software architecture

In addition to the tech stack previously outlined, the software integrates PostgreSQL [35], a robust and reliable relational database management system. PostgreSQL is selected for its extensive feature set, including support for complex data types, advanced indexing, and powerful querying capabilities. By leveraging PostgreSQL, the software can efficiently store and retrieve user data, astronomical images, and associated metadata, ensuring data integrity and reliability. PostgreSQL database schema is shown in Figure 3.

In our software architecture, we've adopted a scalable approach to handling image storage by not storing images directly within the PostgreSQL database. Instead, we store paths or references to the location of the images in the filesystem. This design decision offers several advantages, including flexibility, scalability, and efficient resource management.

By storing paths to images rather than the images themselves, we decouple the storage of data from the database, allowing us to easily transition to alternative storage solutions such as cloud storage providers. This flexibility enables us to adapt to changing storage requirements and seamlessly integrate with existing cloud infrastructure, ensuring optimal performance and reliability.

Furthermore, storing paths to images reduces the storage footprint within the database, resulting in improved database performance and reduced storage costs. It also simplifies the process of managing and backing up data, as only the metadata and references to the images need to be stored within the database.

This approach also enhances data portability and accessibility, as images can be stored in any location accessible to the software, whether on-premises or in the cloud [36]. Users have the flexibility to choose the most suitable storage solution based on their specific requirements, such as cost, performance, and data residency.

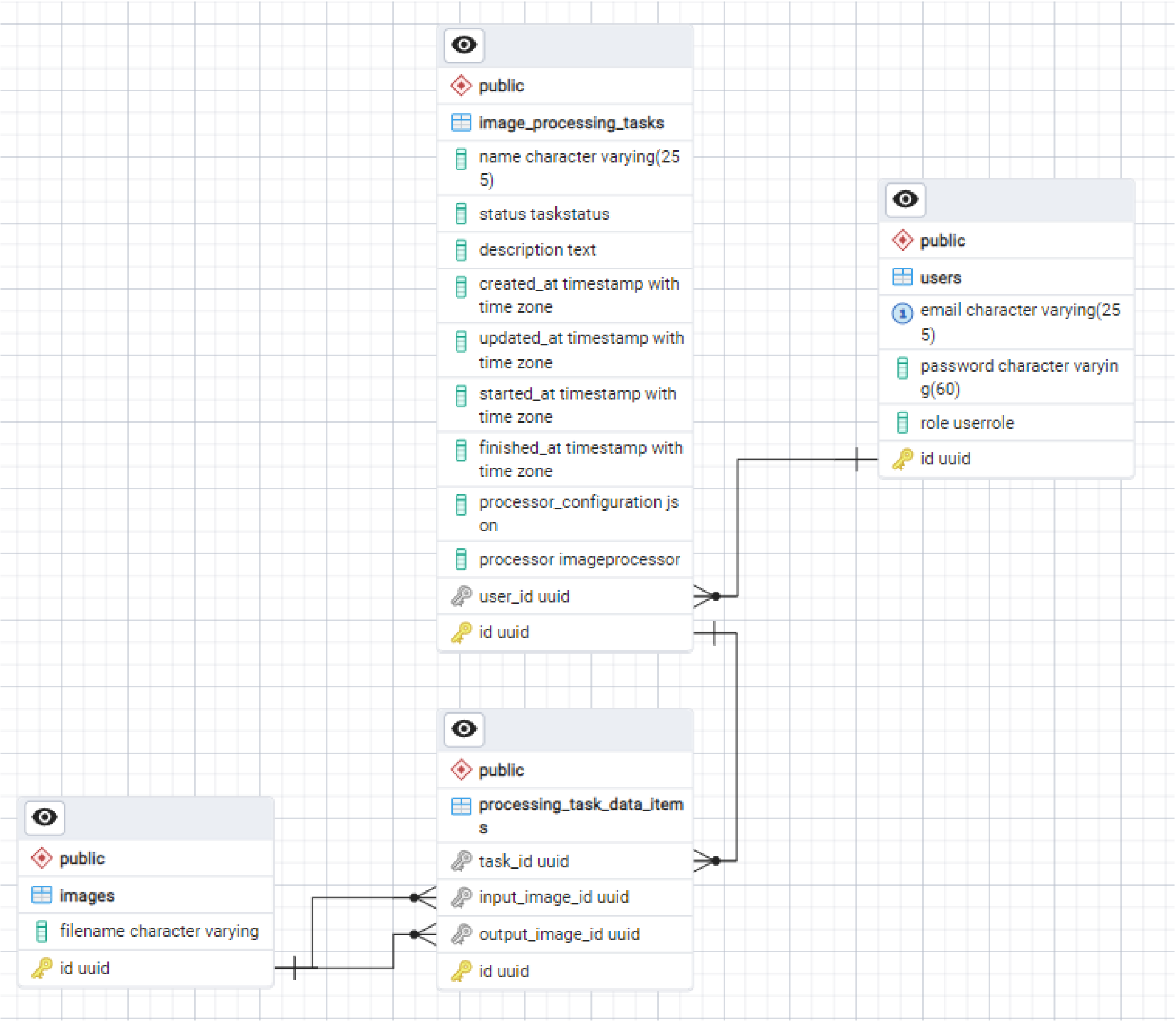


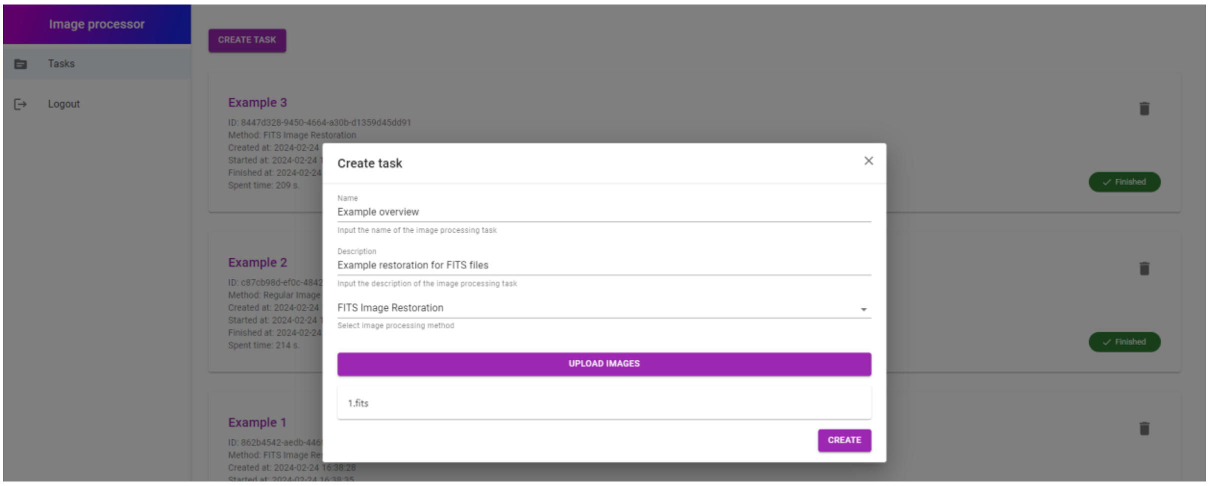
Figure 3: ERD database diagram

Overall, by storing paths to images rather than the images themselves, our software architecture offers a scalable and flexible solution for managing astronomical image data. This approach ensures efficient resource utilization, seamless integration with existing infrastructure, and enhanced data portability, empowering users to analyze and explore astronomical images with ease and confidence.

3.3. WEB-based interface

WEB-based interface allows an end user to use encapsulated Lucy-Richardson implementation under user-friendly HTML web pages. Single objects data mining is performed using following steps:

- image processing task creation with «Fits Image Restoration» method selected on the webpage (see Figure 4);



Example 3
ID: 8447d328-9450-4664-a30b-d1359d45dd91
Method: FITS Image Restoration
Created at: 2024-02-24
Started at: 2024-02-24
Finished at: 2024-02-24
Spent time: 209 s.

Example 2
ID: c87cb98d-ef0c-4842
Method: Regular Image
Created at: 2024-02-24
Started at: 2024-02-24
Finished at: 2024-02-24
Spent time: 214 s.

Example 1
ID: 862b4542-aedb-446
Method: FITS Image Re
Created at: 2024-02-24 16:38:28

Create task

Name
Example overview
Input the name of the image processing task

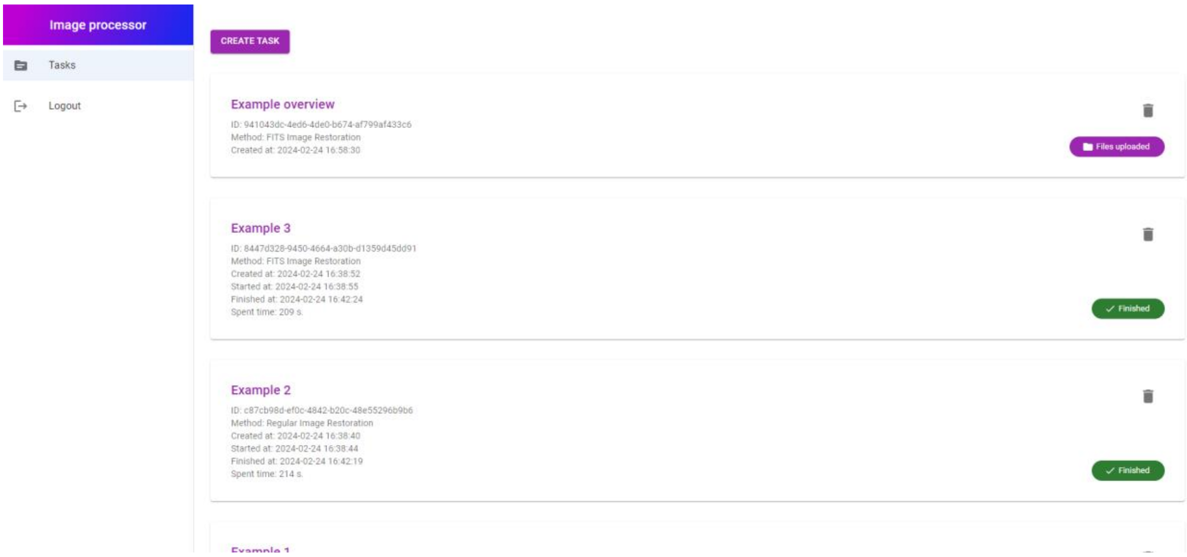
Description
Example restoration for FITS files
Input the description of the image processing task

FITS Image Restoration
Select image processing method

1.fits

Figure 4: Image processing task creation

- new image processing task is shown on a top of the image processing tasks list on the webpage (see Figure **5**);



Example overview
ID: 941043dc-4ed6-4de0-b674-af799af433c6
Method: FITS Image Restoration
Created at: 2024-02-24 16:58:30

Example 3
ID: 8447d328-9450-4664-a30b-d1359d45dd91
Method: FITS Image Restoration
Created at: 2024-02-24 16:38:52
Started at: 2024-02-24 16:38:55
Finished at: 2024-02-24 16:42:24
Spent time: 209 s.

Example 2
ID: c87cb98d-ef0c-4842-b20c-48e55296b9b6
Method: Regular Image Restoration
Created at: 2024-02-24 16:38:40
Started at: 2024-02-24 16:38:44
Finished at: 2024-02-24 16:42:19
Spent time: 214 s.

Figure 5: Created image processing task

- in case we open image processing task page while it is in progress, we will see that there is not output images, it will appear here only once the task finishes its run (see Figure 6);

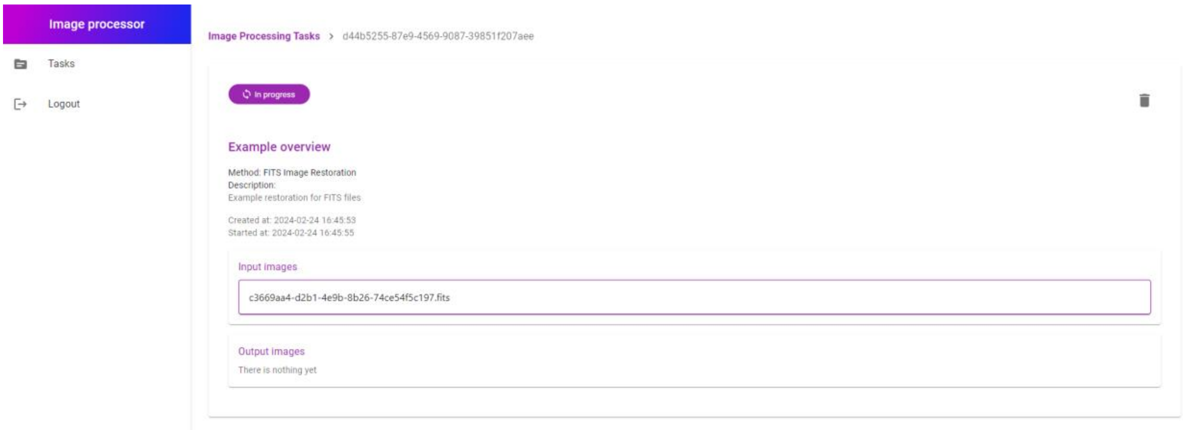


Image Processing Tasks › d44b5255-87e9-4569-9087-39851f207aee

Example overview

Method: FITS Image Restoration
Description:
Example restoration for FITS files

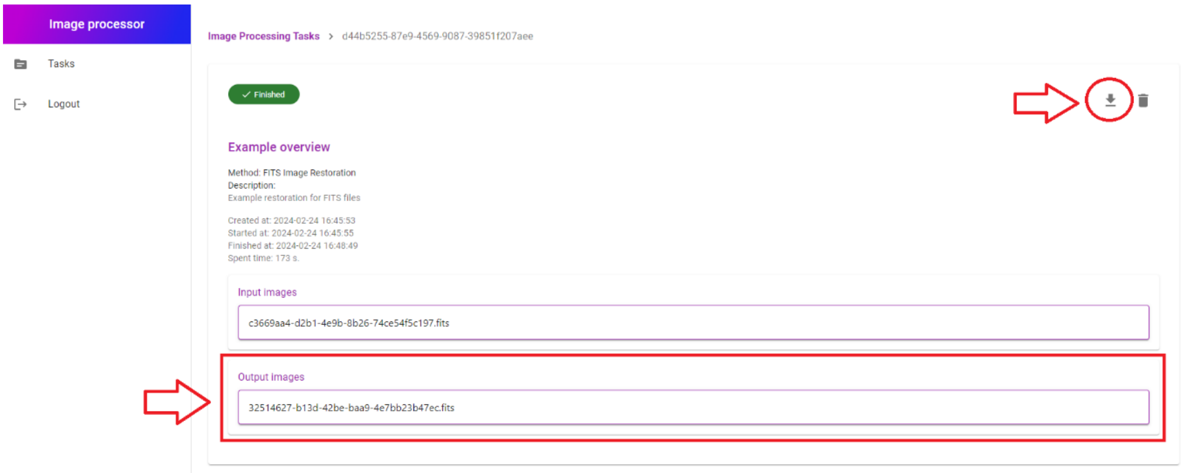
Created at: 2024-02-24 16:45:53
Started at: 2024-02-24 16:45:55

Input images
c3669aa4-d2b1-4e9b-8b26-74ce54f5c197.fits

Output images
There is nothing yet

Figure 6: Image processing task in progress

- once image processing task finishes, we can see output images and download the result as shown on the Figure 7;



Example overview

Method: FITS Image Restoration
Description:
Example restoration for FITS files

Created at: 2024-02-24 16:45:53
Started at: 2024-02-24 16:45:55
Finished at: 2024-02-24 16:48:49
Spent time: 173 s.

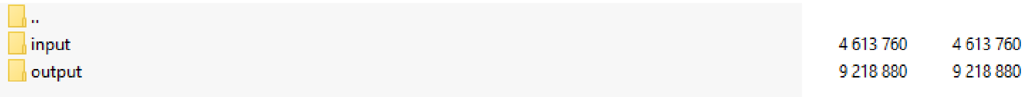
Input images: c3669aa4-d2b1-4e9b-8b26-74ce54f5c197.fits

Output images: 32514627-b13d-42be-baa9-4e7bb23b47ec.fits

Figure 7: Finished image processing task

The interface is intuitive for the end user and does not require any additional steps, which is a definite advantage when working with the software.

Current software solution suggest an output as a structured ZIP archive with two folders: input and output, where each folder contains either input images before restoration (blurred version) or output images (images after Lucy-Richardson algorithm been applied). An example of ZIP archive is shown in Figure 8:



..		
input	4 613 760	4 613 760
output	9 218 880	9 218 880

Figure 8: Example of output ZIP archive

4. Experiment

The object of study are the images of the Solar System objects (SSO) (like stars, asteroids, comets) and any other space objects (like space robots [37], drones [38], satellites [39]) detected in a series of CCD-frames.

The research was conducted in scope of the CoLiTec ((Collection Light Technology) project. This code was implemented at the stage of intra-frame processing of the Lemur software package (Ukraine) [40] for the automated detection of new and maintenance of known objects. The developed implementation was used during the successful identification of CCD frames, which contained a total of more than 800,000 SSOs. Their measurements were also successfully identified with known astronomical catalogs [41].

The initial series for the study were obtained from a variety of telescopes installed at observatories in Ukraine and around the world. Namely, the ISON-NM observatory, the SANTEL-400AN telescope (New Mexico, USA); Vihorlat Observatory, VNT telescope (Humenne, Slovakia) [42]; Odesa-Mayaky Observatory, OMT-800 telescope (Mayaki, Ukraine); Cerro Tololo observatory, PROMPT-8 telescope (La Serena, Chile).

All mentioned above observatories were approved and confirmed by the Minor Planet Center (MPC) as an official organization for the observing and reporting on minor planets or SSOs under the auspices of the International Astronomical Union (IAU).

To verify the developed methods for automated data mining of the single objects from blurred astronomical CCD-frames using the Lucy-Richardson deconvolution in astronomical images, testing was carried out on a series of frames containing more than 1000 frames and above 20,000 measurements.

5. Results

Some image processing results for a blurry frame is given in the Figure 9. We see a blurry frame (left) and output frame after the processing (right) images placed side by side.

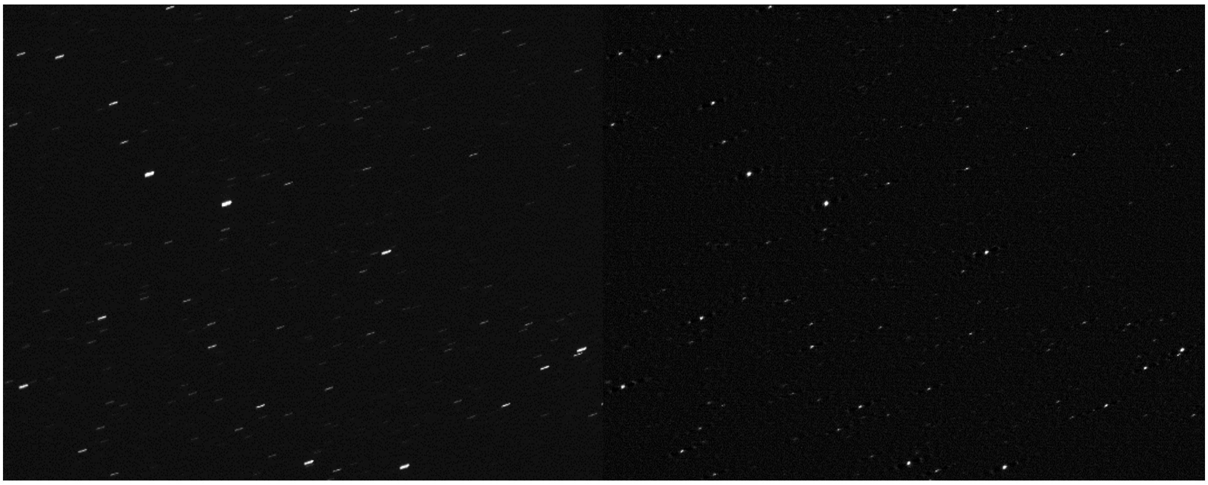


Figure 9: Input and output frames comparison

Zoomed-in frame of a start on a given frame is provided in Figure 10. As we can see the blurry image of a star was restored as well as the aperture brightness value of saturated star images in the original frame.

Restored saturated image of a stars has a minimum level of edges.

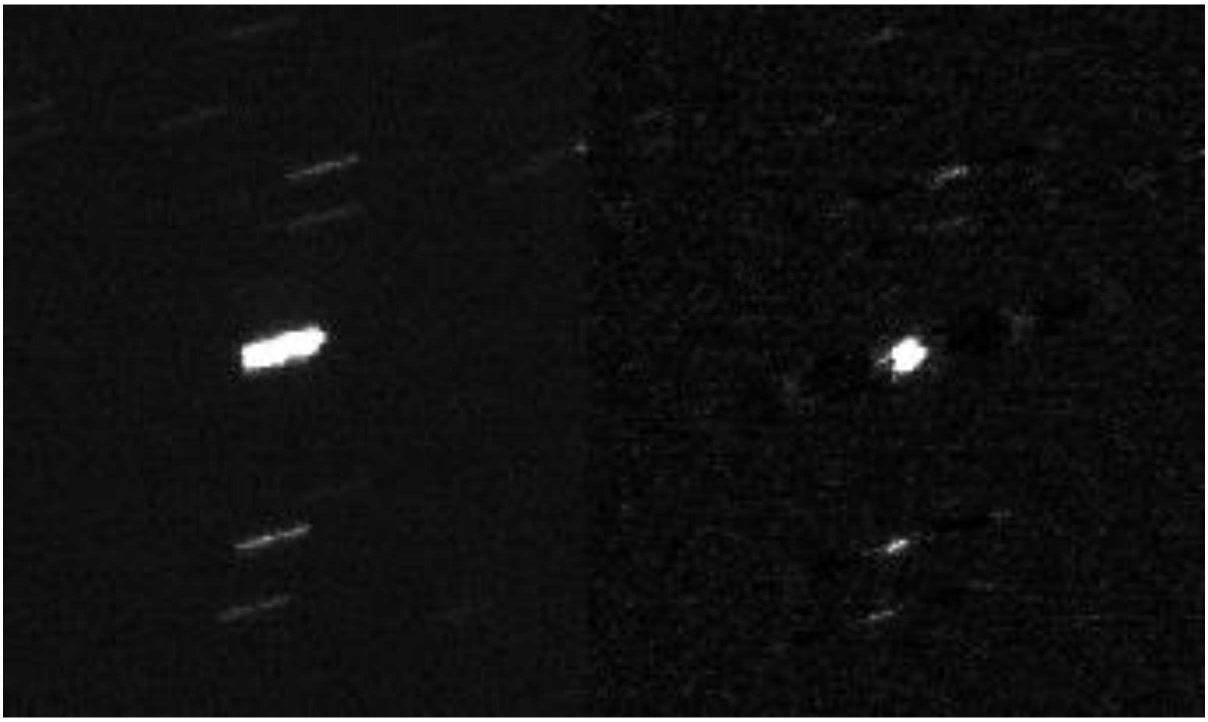


Figure 10: Zoomed-in frame of a start

Given procedure allowed us to increase the signal-to-noise ratio on the reconstructed frame. It allows us to reduce the number of false measurements and increase the accuracy of frame identification, so this method can be applied as the initial data cleaning step before the future processing.

6. Discussions

In the development of the software, significant emphasis was placed on addressing two critical needs in the field of astronomical data analysis and beyond, leading to the implementation of two major advantages over existing solutions.

Firstly, the software introduces an advanced batch processing capability, allowing users to efficiently process multiple images simultaneously [43]. This feature significantly reduces the time and computational resources required for large-scale image analysis, facilitating a more streamlined workflow, and enabling researchers to handle extensive datasets with ease.

Secondly, the software extends its utility beyond the conventional FITS (Flexible Image Transport System) file format [44], which is predominantly used in astronomy, to include a wide array of regular image file types such as JPEG, PNG, etc. This inclusive approach broadens the software's applicability, making it a versatile tool not only for astronomers but also for professionals and enthusiasts in other fields requiring detailed image analysis.

By supporting multiple file types, the software ensures users can directly process images from various sources without the need for preliminary conversion, further enhancing its usability and efficiency.

Unlike FITS files, which are designed to store astronomical images and data with a high degree of precision and can represent a wide range of intensity values, formats like JPEG and PNG encode image brightness on a scale from 0 to 255 [45]. This scale, while sufficient for standard photographic content, often results in celestial images appearing significantly darker or nearly black when viewed without specialized processing. This characteristic stems from the limited dynamic range of these formats, which may not adequately capture the subtle variations in brightness present in astronomical imagery.

However, we were able to resolve this and adapt the algorithm by converting images forward and backward to FITS format and back after processing. The results can be seen in Figure 11 for the regular images.

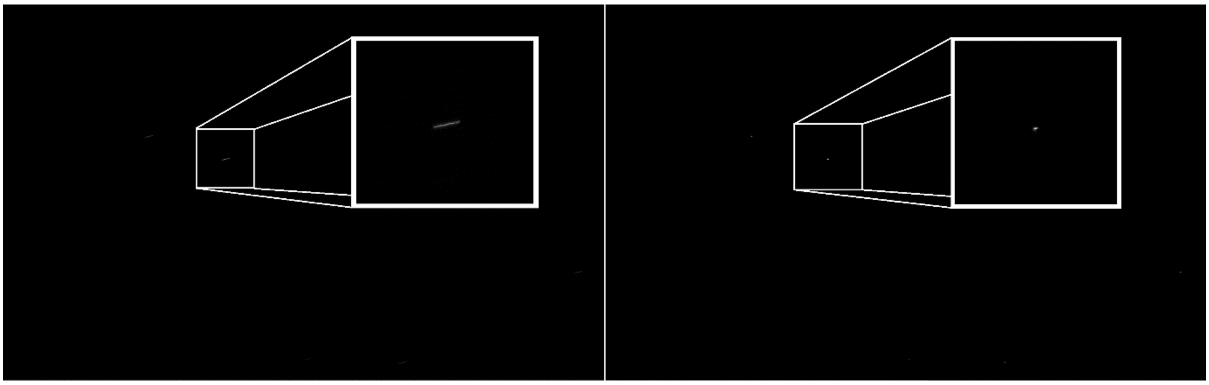


Figure 11: PNG image restoration result

These advancements collectively position the software as a powerful and flexible solution for image processing, catering to a diverse user base and a wide range of applications, from astronomical research to general image analysis tasks.

7. Conclusions

In this paper we presented the details about development as well as application of an innovative method for automated data mining of single objects within blurred astronomical CCD images, employing the Lucy-Richardson deconvolution algorithm for enhanced image restoration.

The extraction of precise data from images affected by various distortions, including atmospheric interference and instrumental limitations, presents a substantial challenge in the field of astronomy. During research we developed a web-based application framework integrating FastAPI, React, Python RQ, and PostgreSQL, designed to facilitate the uploading of blurred images by astronomers and deliver deconvolved, high-resolution images. The implementation of the Lucy-Richardson deconvolution algorithm is central to our approach, offering a robust solution for the reduction of image blur and the recovery of fine details within celestial observations.

Our findings demonstrate significant improvements in image quality and object discernibility, facilitating a deeper analysis of astronomical data. This paper underscores the potential of combining advanced image processing techniques with modern web technology to enhance the field of astronomical research, offering a powerful tool for the accurate identification and analysis of celestial bodies in blurred CCD frames [46].

Expanding upon the existing description, the innovative aspect of this software solution lies in its potential for customization and precision using settings files, which could enable users to fine-tune the image restoration process further. While the current iteration does not permit user manipulation of these settings directly, the architecture of the system is designed with future enhancements in mind.

This would allow for a more tailored approach to the restoration of images, accommodating varying degrees of blur, noise, and other specific challenges inherent in the original files. By integrating a user interface for settings adjustment, the software could offer unprecedented control over the restoration parameters, such as adjusting the intensity of the Lucy-Richardson algorithm or fine-tuning the algorithm's iterations to match the characteristics of the input image.

This perspective opens the door to a more interactive restoration experience, where users can experiment with different settings to achieve the optimal balance between clarity and fidelity to the original image. Such advancements could significantly impact fields reliant on high-precision image analysis/data stream clustering [47], offering a more versatile tool for researchers, photographers, and digital archivists alike. The prospect of integrating these capabilities speaks to the software's forward-thinking design and its commitment to evolving alongside technological advancements.

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References

[1] F. Chierchie, et al., Detailed modeling of the video signal and optimal readout of charge-coupled devices, International Journal of Circuit Theory and Applications, vol. 48, issue 7, pp. 1001-1016, 2020. doi: 10.1002/cta.2784.

[2] V. Troianskyi, P. Kankiewicz, and D. Oszkiewicz, Dynamical evolution of basaltic asteroids outside the Vesta family in the inner main belt, Astronomy and Astrophysics, vol. 672, A97, 2023. doi: 10.1051/0004-6361/202245678.

[3] V. Savanevych, et al., Formation of a typical form of an object image in a series of digital frames, Eastern-European Journal of Enterprise Technologies, vol. 6, issue 2-120, pp. 51–59, 2022. doi: 10.15587/1729-4061.2022.266988.

[4] J. Shu, C. Xie, and Z. Gao, Blind restoration of atmospheric turbulence-degraded images based on curriculum learning, Remote Sensing, vol. 14, issue 19, 4797, 2022. doi: 10.3390/rs14194797.

[5] D. Oszkiewicz, et al., Spins and shapes of basaltic asteroids and the missing mantle problem, Icarus, vol. 397, 115520, 2023. doi: 10.1016/j.icarus.2023.115520.

[6] V. Troianskyi, V. Kashuba, O. Bazyey, et al., First reported observation of asteroids 2017 AB8, 2017 QX33, and 2017 RV12, Contributions of the Astronomical Observatory Skalnaté Pleso, vol. 53, pp. 5-15, 2023. doi: 10.31577/caosp.2023.53.2.5.

[7] S. Cavuoti, M. Brescia, and G. Longo, Data mining and knowledge discovery resources for astronomy in the Web 2.0 age, SPIE Astronomical Telescopes and Instrumentation, Software and Cyberinfrastructure for Astronomy II, vol. 8451, 2012. doi: 10.1117/12.925321.

[8] V. Shvedun, et al., Statistical modelling for determination of perspective number of advertising legislation violations, Actual Problems of Economics, vol. 184, issue 10, pp. 389-396, 2016.

[9] S. Khetkeeree, Optimization of Lucy-Richardson Algorithm Using Modified Tikhonov Regularization for Image Deblurring, J. Phys.: Conf. Ser., vol. 1438, 012014, 2020, doi: 10.1088/1742-6596/1438/1/012014.

[10] V. Akhmetov, et al., Fast coordinate cross-match tool for large astronomical catalogue, Advances in Intelligent Systems and Computing, vol. 871, pp. 3–16, 2019. doi: 10.1007/978-3-030-01069-0_1.

[11] R. Mor, et al., Expanding Big Data mining for Astronomy, XIV Scientific Meeting of the Spanish Astronomical Society, p. 235, 2020. doi: 2020sea..confE.235M.

[12] P. Hasan, and S. N. Hasan, Astronomy data, virtual observatory and education, Proceedings of the International Astronomical Union, vol. 15, issue S367, pp. 151-154, 2019. doi: 10.1017/S174392132100034X.

[13] Ž. Ivezić, et al., Statistics, Data Mining, and Machine Learning in Astronomy: A Practical Python Guide for the Analysis of Survey Data, Princeton University Press, 2019.

[14] J. Bennett, S. Shostak, N. Schneider, and M. MacGregor, Life in the Universe. Princeton University Press, 2022.

[15] I. Vavilova, et al., Surveys, catalogues, databases, and archives of astronomical data, Knowledge Discovery in Big Data from Astronomy and Earth Observation: Elsevier, pp. 57-102, 2020. doi: 10.1016/B978-0-12-819154-5.00015-1.

[16] M. Bellanger, Digital Signal Processing: Theory and Practice. Wiley, 2024.

[17] V. Akhmetov, et al., Astrometric reduction of the wide-field images, Advances in Intelligent Systems and Computing, vol. 1080, pp. 896–909, 2020. doi: 10.1007/978-3-030-33695-0_58.

[18] M. Lösler, C. Eschelbach, and S. Riepl, A modified approach for automated reference point determination of SLR and VLBI telescopes: First investigations at Satellite Observing System Wettzell, Technisches Messen, vol. 85, pp. 616–626, 2018. doi: 10.1515/teme-2018-0053.

[19] S. Minaee, Y. Y. Boykov, F. Porikli, et al., Image Segmentation Using Deep Learning: A Survey, IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 44, issue 7, pp. 3523-3542, 2021. doi: 10.1109/TPAMI.2021.3059968.

[20] M. Dadkhah, V. V. Lyashenko, Z. V. Deineko, et al., Methodology of wavelet analysis in research of dynamics of phishing attacks. International Journal of Advanced Intelligence Paradigms, vol. 12, issue 3-4, pp. 220-238, 2019. doi: 10.1504/IJAIP.2019.098561.

[21] L. Kirichenko, A.S.A. Alghawli, T. Radivilova, Generalized approach to analysis of multifractal properties from short time series, International Journal of Advanced Computer Science and Applications, vol. 11, issue 5, pp. 183–198, 2020. doi: 10.14569/IJACSA.2020.0110527.

[22] K. Hampson, et al., High precision automated alignment procedure for two-mirror telescopes. Applied Optics, vol. 58, pp. 7388–7391, 2019. doi: 10.1364/AO.58.007388.

[23] I. Kudzej, et al., CoLiTecVS – A new tool for the automated reduction of photometric observations, Astronomische Nachrichten, vol. 340, pp. 68–70, 2019. doi: 10.1002/asna.201913562.

[24] S. Khlamov, et al., Development of computational method for matched filtration with analytic profile of the blurred digital image, Eastern-European Journal of Enterprise Technologies, vol. 5, issue 4-119, pp. 24–32, 2022. doi: 10.15587/1729-4061.2022.265309.

[25] W. Burger, and M. Burge, Digital image processing: an algorithmic introduction, Springer Nature, 945 p., 2022. doi: 10.1007/978-3-031-05744-1.

[26] V. Savanevych, et al., Mathematical methods for an accurate navigation of the robotic telescopes, Mathematics, vol. 11, issue 10, 2246, 2023. doi: 10.3390/math11102246.

[27] J. Peng, L. Xiyu, L. Zhengyang, et al., Point spread function modelling for wide-field small-aperture telescopes with a denoising autoencoder, MNRAS, vol. 493, pp. 651-660, 2020. doi: 10.1093/mnras/staa319.

[28] I. L. Andronov, et al., Algorithm of the artificial comparison star for the CCD photometry, Astronomical School's Report, vol. 5 (1-2), pp. 264–272, 2004. doi: 10.18372/2411-6602.05.1264.

[29] L. Mykhailova, et al., Method of maximum likelihood estimation of compact group objects location on CCD-frame, Eastern-European Journal of Enterprise Technologies, vol. 5, issue 4, pp. 16-22, 2014. doi:10.15587/1729-4061.2014.28028.

[30] R. F. H. Torres, R. Garcia, Image Restoration for Blurred License Plates Extracted from Traffic Video Surveillance using Lucy Richardson Algorithm, in: IEEE 14th HNICEM, Boracay Island, Philippines, pp. 1-6, 2022. doi: 10.1109/HNICEM57413.2022.10109437.

[31] Z. He, H. Wang, et. al., A Deconvolutional Reconstruction Method Based on Lucy–Richardson Algorithm for Joint Scanning Laser Thermography, in: IEEE Transactions on Instrumentation and Measurement, vol. 70, 4501508, pp. 1-8, 2021, pp. doi: 10.1109/TIM.2020.3034967.

[32] Python 3.12.2 documentation. Available at: https://docs.python.org/3.

[33] Python RQ documentation. Available at: https://python-rq.org/docs.

[34] M. H. Ibrahim, M. Sayagh, and A. E. Hassan, A study of how Docker Compose is used to compose multi-component systems, Empirical Software Engineering, vol. 26, 128, 2021. doi: 10.1007/s10664-021-10025-1.

[35] H. Schönig, Mastering PostgreSQL 15: Advanced techniques to build and manage scalable, reliable, and fault-tolerant database applications, 5th ed., Packt Publishing Ltd, 2023.

[36] C. L. Albarracín, S. Venkatesan, A. Y. Torres, et al., Exploration on Cloud Computing Techniques and Its Energy Concern, Mathematical Statistician and Engineering Applications, vol. 72, issue 1, pp. 749-758, 2023. doi: 10.17762/msea.v72i1.2022.

[37] A. Tantsiura, et al., Evaluation of the potential accuracy of correlation extreme navigation systems of low-altitude mobile robots, International Journal of Advanced Trends in Computer Science and Engineering, vol. 8, issue 5, pp. 2161–2166, 2019. doi:10.30534/ijatcse/2019/47852019.

[38] N. Yeromina, V. Tarshyn, S. Petrov, et al., Method of reference image selection to provide high-speed aircraft navigation under conditions of rapid change of flight trajectory, International Journal of Advanced Technology and Engineering Exploration, vol. 8, issue 85, pp. 1621–1638, 2021. doi:10.19101/IJATEE.2021.874814.

[39] V. Akhmetov, et al., Cloud computing analysis of Indian ASAT test on March 27, 2019, in: IEEE PIC S and T, pp. 315–318, 2019. doi: 10.1109/picst47496.2019.9061243.

[40] Lemur software, CoLiTec project. Available at: https://colitec.space.

[41] V. Akhmetov, et al., New approach for pixelization of big astronomical data for machine vision purpose, IEEE International Symposium on Industrial Electronics, pp. 1706–1710, 2019. doi: 10.1109/ISIE.2019.8781270.

[42] Š. Parimucha, et al., CoLiTecVS – A new tool for an automated reduction of photometric observations, Contributions of the Astronomical Observatory Skalnate Pleso, vol. 49, issue 2, pp. 151-153, 2019. doi:2019CoSka..49..151P.

[43] J. X. Prochaska, J. F. Hennawi, K. B. Westfall, PypeIt: The Python Spectroscopic Data Reduction Pipeline, 2020, pp. doi: 10.48550/arXiv.2005.06505.

[44] W. D. Pence, L. Chiappetti, C. G. Page, R. A. Shaw, and E. Stobie, Definition of the flexible image transport system (fits), version 3.0, Astronomy & Astrophysics, vol. 524, A42, 2010. doi: 10.1051/0004-6361/201015362.

[45] J. Ascenso, E. Alshina, and T. Ebrahimi, The JPEG AI standard: Providing efficient human and machine visual data consumption, Ieee Multimedia, vol. 30, issue 1, pp. 100-111, 2023. doi: 10.1109/MMUL.2023.3245919.

[46] M. Faaique, Overview of Big Data Analytics in Modern Astronomy, Int. Journal of Mathematics, Statistics, and Computer Science, vol. 2, pp. 96–113, 2023. doi: 10.59543/ijmscs.v2i.8561.

[47] Zhernova, P. Data stream clustering in conditions of an unknown amount of classes [Text] / P. Zhernova, A. Deyneko, Zh. Deineko, I. Pliss, V. Ahafonov // Advances in Intelligent Systems and Computing. – 2019. – Vol. 754. – P. 410–418. doi: 10.1007/978-3-319-91008-6_41.