Introduction

Quartus Engineering Incorporated (Quartus) is an engineering services and system development company which uses simulation-driven engineering to solve challenging problems for clients. In our optical systems group, we leverage expertise in computer vision, image processing, and optics in a multi-disciplinary team to address client needs. We have a long history of developing custom metrology software and algorithms for the purpose of characterizing imaging systems. This includes areas such as: geometric calibration, PSF estimation, flat field correction, dark noise characterization, field curvature, etc. In addition to expertise in modelling and estimating parameters of imaging systems, we have done a significant amount of work in the areas of image processing and computer vision, more generally, to solve detection and estimation problems. This computer vision experience ranges from classical feature engineering-based approaches, to convolutional neural network-based approaches. We believe that careful study of the problem domain is key to finding the right approach. In this exoplanet detection problem, we believe that classical computer vision techniques can be combined with a model-based approach derived from studying the optical simulations that have been developed for the Starshade program.

Proposed Approach

The proposed approach will leverage the detailed modelling which has been performed in the SISTER project[1]. The proposed approach to planet detection and spectral estimation can be described in a few high-level steps: background estimation and removal, image transformation, and Bayesian detection. A block diagram of the proposed approach is shown below.

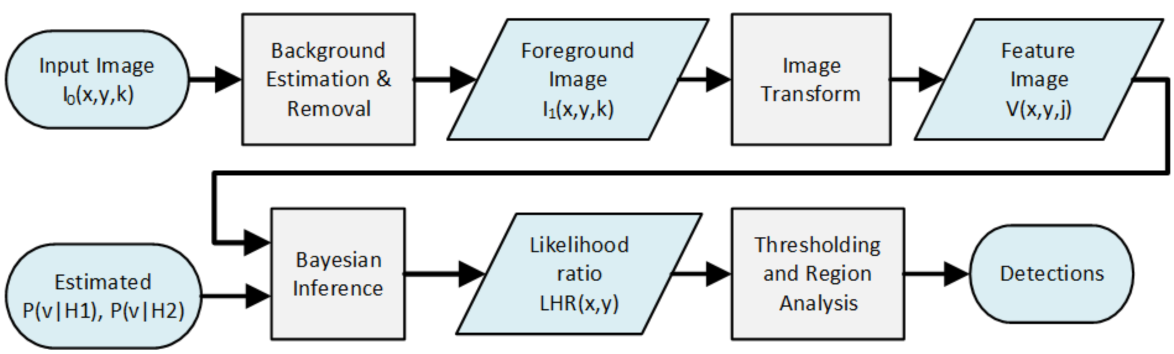

Figure 1. Block diagram of proposed approach. Input image $I_0(x,y,k)$ is assumed to be a multi-spectral image where x,y are pixel position, and k is spectral channel index. P(v|H1) and P(v|H2) are estimated multivariate probability distributions defined on feature vector v.

Background Estimation and Removal

Background estimation and removal is an important sub-problem in image processing for astronomical images. Prior work in background estimation for complex background structures focuses on complex extended structures such as nebula[2]. In the Starshade direct imaging application, the dominant background sources are solar glint and exozodiacal light[3]. These background sources may include large gradients, and may dominate signals from planets, therefore existing background estimation techniques may be of limited utility for dim planets close to their corresponding star. A baseline background subtraction performance will be established by using the SExtractor background estimation method developed by Bertin & Arnouts[4]. An alternative model-based approach is proposed for estimating and subtracting the solar glint. The SISTER project[1] uses a parametric model of the solar glint including parameters such as: solar angle, and radius of the circular section of the starshade. This parametric model can be leveraged to estimate the solar glint by solving an optimization problem which finds parameters to minimize error with the observed image. The cost function can be designed to compute errors directly in pixel space using an M-estimator weighting scheme such that unmodeled content such as planets are not weighed heavily in fitting the solar glint. A brief study will be performed on a number of free parameters and initial conditions, assuming some parameters are known a priori. Some investigation of cost function and M-estimator weighting function is warranted. After estimation, the solar glint can be subtracted from the scene. Background from exozodiacal light and other sources will still be unaccounted for, but these sources being more diffuse may allow them to be handled reasonably well by SExtractor. Some study will be required on tuning SExtractor parameters for background estimation.

Image Transformation

It is assumed that for each star-planet system, multispectral images are captured with N channels. It is further assumed that planets behave as point-like sources. The goal of the image transformation step is to transform the multispectral image into a feature space where each pixel location is associated with a multi-dimensional feature vector. This general approach of image transform as a pre-processing step is described by M. Masias et al 2012[5].

The proposed design of the feature space for this particular application aims to exploit the fact that planets are generally point-like sources, and furthermore that their spectral characteristics tend to vary compared to background. The design of the feature space is intended to cause planets to cluster in the feature space in a distribution that separates planet pixels from background pixels, such that the respective probability distributions in feature space lend themselves to later Bayesian analysis. The proposed transformation from the multispectral image to feature space has the following steps:

1. Apply a MF(matched-filter) to each image channel, where the MF is the PSF of the imaging system. The MF approach is generally recommended for detection of point sources[6].
2. Take the filtered multispectral image, compute total intensity per-pixel and store this as an intensity image. Use the intensity image to perform a pixel-wise normalization of the multispectral image channels, such that each pixel represents a unit 'color vector'.
3. Next the goal is to create a feature to measure local rate of change in spectral characteristics. The proposed feature descriptor for local spectral change is to compute an average 'cosine distance'(or 1 – cosine similarity) between each pixel and it's 4-connected neighborhood. This is analogous to a Laplacian filter, but using the cosine distance between neighboring pixel 'color vectors' as a multidimensional distance measure.

The transformed image in the proposed feature space will consist of the filtered intensity channel from step 2, combined with the measure of spectral change from step 3. This set of feature vectors can be referred to as $V(x, y, i)$, where x,y represent pixel position, and i represents feature index. Optionally, the two feature descriptor channels may be appended with the normalized spectral channels in case a priori knowledge is available about the probability distribution of planetary spectral characteristics vs. background spectral characteristics.

Bayesian Detection

The final step in the proposed detection pipeline for multispectral images is Bayesian inference and detection. Bayesian inference has broad applications for detection problems. In particular the Bayes decision rule provides the optimal decision rule for any detection problem under certain distributional assumptions[7]. The proposed application of Bayesian inference is as follows: Let the observed feature vector at a given pixel location be v. Let the hypothesis that a pixel corresponds to a planet be $H1$, and let the hypothesis that a pixel corresponds to background be $H2$. The proposed approach is to compute the likelihood ratio for each pixel as a function of v:

$$LHR(v) = \frac{p(v|H1)}{p(v|H2)} \tag{1}$$

Where $p(v|H1)$, and $p(v|H2)$ are multivariate probability distributions which must be characterized. It is proposed to use the SISTER library[1] to generate a number of scenarios, pass the images through background removal and feature transform, measure histograms of $p(v|H1)$ and $p(v|H2)$, and use the histograms to estimate multivariate normal distributions. These estimated distributions can then be used to compute $LHR(x, y)$, at each pixel location yielding a likelihood ratio map for the multi-spectral image. The next step is to apply threshold th to the $LHR(x, y)$, to yield a binary image $B(x, y) = LHR(x, y) > th$. If the prior odds ratio $p(H1)/p(H2)$ is known, the th can be chosen to yield the Bayes decision rule for minimum probability of error. If the prior odds ratio is not known, the threshold can be tuned empirically to arrive at some desired true positive rate.

Application of the threshold to the LHR map will yield a binary image of positive detections, and it is expected that each planet may yield multiple positive detections in a connected region of pixels. A connected component analysis will be performed to assign a separate ID to each connected region in the binary image $B(x, y)$. Average spectral content will be computed for each connected component, yielding an estimate of spectral properties for that particular planet. A sub-pixel estimate of planet location will also be computed by taking a weighted centroid of the LHR within a connected pixel region associated with the detection of a single planet. The final output of this connected component analysis will therefore be a list of detected planets with sub-pixel locations and average spectral values from pixels associated with the planet.

Extension to Multiple Images and Multi-Epoch Observations

The proposed method can be extended to handle repeat images of the same star-planet system by using an appropriate image stacking method to combine the images into a single composite with improved SNR before applying the method. If multi-epoch measurements are available such that significant planetary motion may be observed, an additional layer of modelling and estimation is proposed. This additional modelling layer would use RANSAC with Keplerian orbital models to find correspondences between planets detected across several images. A distance measure in both pixel space and spectral properties may be used for inlier detection. After sample consensus with orbital models, a final estimation step would optimize orbital parameters. This additional modelling layer with multi-epoch data could provide increased sensitivity and specificity, since positive planet detections can also be required to fit a reasonable Keplerian orbit.

Data Products

Initial algorithm outputs for all synthetic images received for the data challenge will be delivered within five months of receiving the synthetic images. A final set of algorithm outputs will be delivered with the final report by September 2021, in addition to other deliverables listed in the cost summary below. The outputs will consist of: background estimates(with dust and solar glint components), planet detections with per-planet properties(location, brightness, spectral characteristics), and estimated orbital parameters in the case of multi-epoch data. Output data will be delivered as .mat files, or an alternative scientific data format if desired.(e.g. HD5)

References

1. Rafels, S. H., Shaklan, S. B., Turnbull, M. C., & Cady, E. J. (2019). SISTER: Starshade Imaging Simulation Toolkit for Exoplanet Reconnaissance (Conference Presentation). *Techniques and Instrumentation for Detection of Exoplanets IX*. doi:10.1117/12.2528332
2. Popowicz, A., & Smolka, B. (2015). A method of complex background estimation in astronomical images. *Monthly Notices of the Royal Astronomical Society*, *452*(1), 809-823. doi:10.1093/mnras/stv1320
3. Seager, Sara, Kasdin, Jeremy, Starshade Rendezvous Probe Team (2018). “Starshade Rendezvous Mission Probe Concept”. *American Astronomical Society, AAS Meeting #231, id. 121.09*
4. Bertin, E., Arnouts, S. (1996). SExtractor: Software for source extraction. *Astronomy and Astrophysics Supplement Series, 117(2), 393-404. doi:10.1051/aas:1996164*
5. M. Masias, J. Freixenet, X. Lladó, M. Peracaula, A review of source detection approaches in astronomical images, Monthly Notices of the Royal Astronomical Society, Volume 422, Issue 2, May 2012, Pages 1674–1689, doi:10.1111/j.1365-2966.2012.20742.x
6. Vio, R., Andreani, P., & Wamsteker, W. (2004). Some good reasons to use matched filters for the detection of point sources in CMB maps. *Astronomy & Astrophysics, 414(1), 17-21. doi:10.1051/0004-6361:20031632*
7. Hastie, T., Friedman, J., & Tisbshirani, R. (2017). The Elements of statistical learning: Data mining, inference, and prediction. New York, New York: Springer.

Brian Dunne

Experience

Quartus Engineering Inc., San Diego, CA **2/2016-present**

Titles Held: *Electrical Engineer, Project Engineer, Senior Engineer, Engineering Manager*

- Filled technical leadership role for multiple projects, and provided mentorship for other members of the electrical and software engineering team.
- Developed machine vision and visual servoing software for industrial automation based on real-time feedback from 3D cameras.
- Developed various image processing algorithms and associated software for optical metrology, calibration, and test for consumer electronics.
- Developed software for performing automated alignment of optical components. The software was developed with C# and the .Net Framework.
- Developed and maintained a MATLAB library for geometric camera calibration.

Independent Contractor **12/2013-11/2014**

Algorithm Engineer (under contract with Vaporsens) 6/2014-11/2014

- Developed classification algorithms and data analysis tools for a novel sensor array for gas-phase chemical detection. Maintained a database of sensor data and used it to train and test algorithms.

Electrical Design Engineer (under contract with Zymbit) 12/2013-5/2014

- Designed electronics for a hardware platform targeted at Internet of Things applications.

Spectrafluidics Inc., Santa Barbara, CA **7/2009-10/2013**

Titles Held: *Electrical Design Engineer, Research Engineer*

- Invented and implemented a novel MEMs sensor required for automating a microfluidic chemical sensing technique.
- Developed software used for operation and testing of the chemical sensing system. This included sophisticated automation solutions for various subsystems drawing upon techniques from computer vision, spectroscopy, controls and signal processing.
- Developed spectral classification algorithms using techniques from signal processing, multivariate analysis, machine learning, and detection theory.

Skills

Areas of Proficiency: computer vision, signal and image processing, machine learning, detection theory, control theory, statistics.

Software Development: Fluent in: Python, MATLAB, C#, C++, C. Experience with: R, Java, Labview.

Electronics Design: microcontrollers, embedded systems, analog and digital design.

Education

University of California, San Diego **9/2014-12/2015**

M.S. in Electrical Engineering

- Intelligent Systems, Robotics, and Control
- Signal and Image Processing

University of California, Santa Barbara **9/2005-6/2009**

B.S. in Electrical Engineering

Dr. Ashkan Arianpour

Experience

Quartus Engineering Inc., San Diego, CA **3/2015-present**

Titles Held: *Optical Engineer, Project Engineer, Engineering Manager*

- Lead Engineer and System Architect for a wide variety of optical systems ranging from biomedical, aerospace, LIDAR, optical communications, and consumer products.
- Recorded and developed large aperture holographic scanners for airborne LIDAR systems. Designed optical systems for tracking and controlling platforms with resolution of less than 50nm. Developing and leading the system architecture for a large aperture adaptive optic system.
- Designed, system engineered, built, and deployed a free-space adaptive optical communication system
- Provided mentorship and guidance to optical and optomechanical engineers

University of California San Diego **9/2008-3/2015**

Graduate Student researcher

- Developed and published a DARPA sponsored 2.8x telescopic and switchable contact lens for patient's suffering from macular degeneration
- Designed, developed, and published a Google sponsored wide-field monocentric optic with an embossed microprism array in a fiber coupled imaging system. train and test algorithms.
- Designed, developed, and published a DARPA sponsored optomechanical fluid filled eye model with a pseudo-retina in the form of a curved-input fiber bundle with a 34° field of view as a testing apparatus for vision based optics (intraocular lenses, contact lenses, HMDs, etc).

Skills

Areas of Proficiency: Optical design and analysis, system engineering, optical alignment, atmospheric modeling, electro-optic system.

Software Development: Fluent in: MATLAB, ZPL Macro

Education

University of California, San Diego **1/2010-3/2015**
Ph.D. in Photonics Engineering

- Vision and Wide Field Imaging

University of California, San Diego **9/2008-1/2010**
M.S. in Photonics Engineering

- Biomedical Optics and Vision

University of California, San Diego **9/2002-6/2007**
B.S. in Electrical Engineering

Cost Summary

The Quartus accounting system is not is not adequate for accumulating costs.

Quartus proposes to perform this work and provide deliverables for a total cost of **$49,902.14,** where deliverables include:

1. Participation in Starshade Data Challenge Teleconferences, which will be nominally monthly during the performance period.
2. A Final Report by September 2021 along with abstracts of papers submitted and descriptions of derived data products delivered. The report shall include a summary of research activities and findings to date, a bibliography of papers submitted, descriptions of derived data products to be delivered, and a figure that illustrates the investigation or results obtained.
3. A final version of algorithms in a form suitable for archiving on the ExEP's starshade technology website.
4. Electronic copies of all technical papers published as a result of this work.

Response to **Cost Instructions - 1.0 Data Submittal - paragraph 1.1**

See attached form A-19 for a cost elements breakdown.

Response to **Cost Instructions - 1.0 Data Submittal - paragraphs 1.2, 2.0 and 3.0**

See attached form A-19 for a cost elements breakdown. Additional information responding to paragraphs 2.0 and 3.0 can be provided upon request.

Response to **Cost Instructions – 1.0 Data Submittal – paragraphs 7.1,7.2 and 7.3**

Financial data responding to 7.1 is included in the attached document. Paragraph 7.2 is not applicable. In response to paragraph 7.3, Group A attachments are included in the attached document.

Contact Information

Customer

Name	Title/Role	Email	Phone
Maria Jacquez	Subcontracts Manager	Maria.A.Jaquez@jpl.nasa.gov	818-354-2839

Quartus Engineering

Name	Title/Role	Email	Phone
Brian Dunne	Engineering Manager	brian.dunne@quartus.com	562-299-2474
Andrea Cuneo	Contracts	andrea.cuneo@quartus.com	858-875-6988

Approval

X Brian Dunne 10/15/2020

Brian Dunne – Engineering Manager