Interim Review

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November 2023

1 Introduction

Particle Tracking Velocimetry (PTV) is a technique to determine a flow field and its accompanying flow derivatives. This is frequently done by using high-speed cameras and high repetition rate lasers, and computational methods [4] to determine the positions of the particles at various time steps. From this, information like velocities, accelerations and pressure fields can be deduced. Particle Image Velocimetry (PIV) is another related technique, that finds use in a range of fields, such as the development of boundary layers in adverse pressure gradients, helicopter aerodynamics, and more. It has a variety of advantages over other methods of studying flows. Hot-wire anemometry can only measure a point in a flow, whereas PIV is able to capture the whole flow field. CFD can estimate a flow field, however approximations during linearisation and the risk of human operators using the system incorrectly means that flow physics may be incorrect. PIV makes no approximations, because the flow is a real flow.

The equipment used comes at a steep cost, and the monochromatic nature of lasers means that there is plenty of sensing capability left on the camera sensor. Work has been done on using color to encode spatial and temporal information in PIV, however this remains under-utilised in PTV methods. Doing this would dramatically reduce costs through the use of lower-end cameras. Using wavelength to encode depth means that 3 dimensional, 3 component (3D3C) velocity vectors can be found with just one camera [6], as opposed to the typical minimum of two cameras. To get time-resolved information, the traditional method of repeated image capture is still necessary, meaning high light intensity and high-speed cameras for high-speed flows.

1.1 Colour spill

Much work has been done surrounding temporal information through colour. In Wang, 2017[5], RGB pulses are used at different times during a camera's exposure to capture three different views into the same flow field. Something that is discussed in this work as well as numerous others is that a red illumination pulse does not only activate the red channels of a camera, it also illuminates the green and blue channels to some degree. This is because the spectral response of a camera sensor will have overlapping wavelengths. I will refer to this effect as colour spill. Not reducing colour spill will affect the results of any particle tracking system that doesn't account for it, and multiple methods have been suggested to reduce the errors it will induce. Wang et al. suggests finding a transfer function from the intensity of each channel to the other channels of an image. In [2], Aruga et al. suggests finding the correlation coefficient of each channel for a particular peak, and treating the particle as appropriate. The method used by Aguirre-Pablo et al. [1] cuts off low intensity signals, as this worked well in their specific setup. If left uncorrected, this will likely lead to ghost particles and decreased positional accuracy, much like the effects of noise in Shake-The-Box[4], an algorithm for tracking particles which will be discussed further in Section 1.2. This will be through the increased presence of ghost particles. Each of these methods has benefits and drawbacks.

The method in [2] is effective for their setup, where colour spill only affects the blue channel on their two-colour setup. One downside that they mention is that high particle densities do not work with this method, as there may be high correlation coefficients. This is because there will be particles that are overlapping, rather than because of colour spill.

The method laid out in [5] paper is more robust. In this paper, intensities from the peaks are plotted against each other, and then a quadratic curve is fit to the data. This allowed for the intensities from the camera to be related to intensities from each time step. This method does result in multiple solutions, however there is only one solution with a clear physical interpretation that is used.

Truncating small values is a method that clearly works for the system in [1] However, this is a method that may be more prone to error. It also relies on a particular imaging system, so it is not clear that it can be assumed that my imaging setup will work with this method.

[5]'s method of correcting colour spill will be used for my work. This is because it will likely work in more situations than [1] and it can tolerate higher concentrations of particles than [2]. These are important requirements for my system, as higher particle concentrations give a better refined velocity field. The end goal of this project is a cheap, scalable PTV system. As technology increases, the optical system will change. This means that while truncating low intensities may work now, this may not be true for future systems with the ideal hardware of the future.

As was previously mentioned, an increase in the number of ghost particles will mean worse accuracy in the results. In PIV systems, this is less of an issue as they rely on the bulk motion of a small area as compared to the motion of an individual particle. If the colour spill removal is mostly tuned but still leaves a small amount of spill, it is possible that the tracking algorithm will treat this small peak as noise. It is demonstrated in [4] that the algorithm is quite resistant to artificial noise, so it is likely that imperfect colour spill removal will be close to good enough. However, these remaining peaks will behave differently to typical noise, because they follow the trajectory of particles, rather than being randomly distributed. The effects of this will be studied throughout the work.

1.2 Shake-The-Box

Shake-The-Box is a Lagrangian Particle Tracking algorithm, described by Schanz et al. in [4]. It improves on PIV systems through tracking individual particles, rather than a small volume of particles. It gives better positional accuracy, higher particle seeding concentrations, and better noise resistance than SMART, a PIV system. It has mostly only been used with high-speed cameras and lasers up until now, and hopefully this work should allow further work to be done using LEDs and low-cost sensors.

1.3 Particle Shadow Velocimetry

Unlike other methods, where light is reflected off the particles and into the camera sensor, the method used here will be illuminating the particles from behind and recording their shadows. This is a method known as Particle Shadow Velocimetry (PSV) and it is a way to reduce the needed intensity of light as described by Estevadeordal and Goss in [3], thereby allowing lower-power LED illumination to be used. In [1], some image processing is done to remove the effects of inhomogenous background lighting, as well as to convert the white background and cyan, magenta and yellow peaks into a black background and red, green and blue peaks. I will likely have to do similar processing on my data.

2 Methods

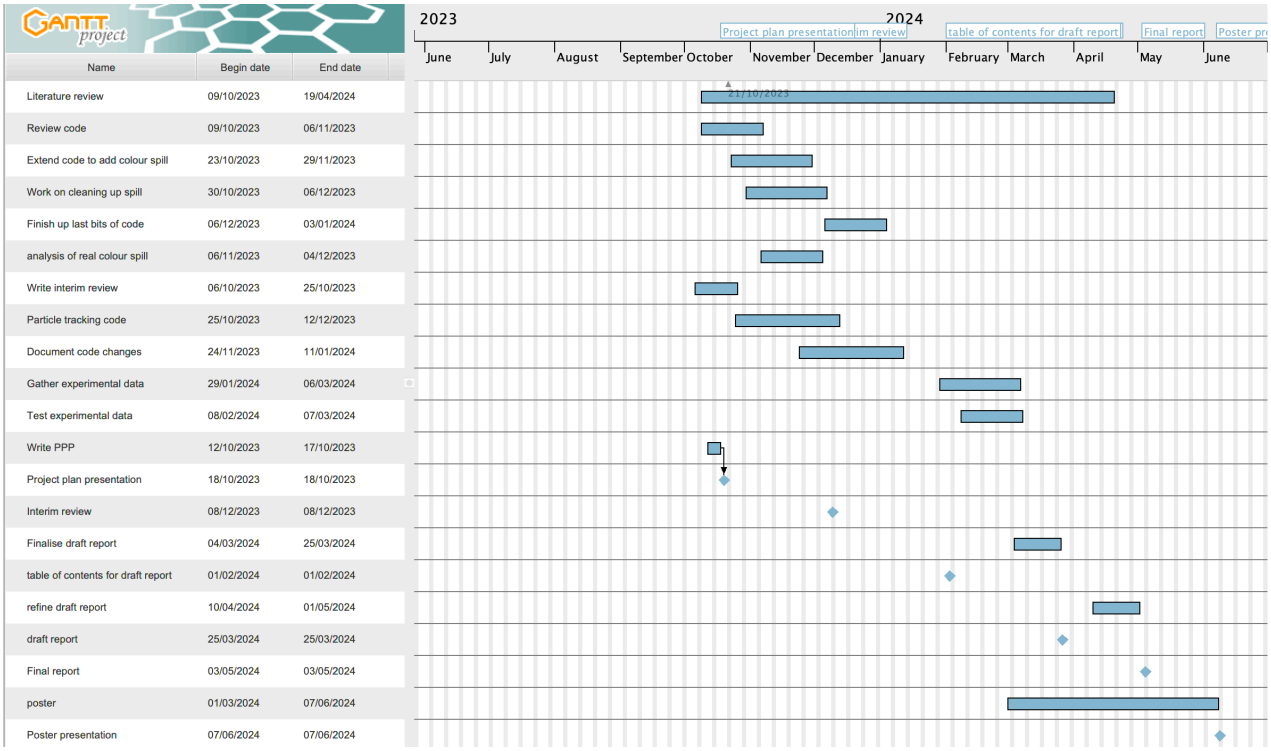
In the rest of my work, I will aim to find how much of an issue colour spill is for particle tracking, and how I can effectively mitigate it. To do this, I will add colour spill into Gigatrack, and compare results with and without colour spill. I will then attempt to implement measures to reduce the effect of colour spill. Finally, this is no use without testing on real data and its difficulties. For this, real world testing will be done and the results evaluated.

To implement Wang's method, I will use test data sent from the manufacturer of the equipment that will be used. This comes in the form of multiple monochromatic images. From these images, the correlation between the intensity of one colour channel and another can be established. This method is similar to what was done in [5]. This is in contrast to other work, which took images as if the experiment was running but with no fluid motion [1]. Assuming that the effect of each layer on each other layer is linear, this should be fine Once these transfer functions are generated, the inverse of them can be found and through this, colour spill can be added into the existing synthetic image generation code in Gigatrack. This colour spill will have to be undone for the particle tracking to work. This should be fairly similar to adding the effects of colour spill into the image generation.

To verify that my system works, I will use the reconstruction of the synthetic data to compare the code with colour spill to the code without colour spill. Some metrics I will test are ghost particle fraction, mean position error and fraction of untracked particles. These can be tested against the results in [4] to validate that the system is working as expected. These can only be done for synthetic images, because by generating the images, the actual position of every particle at every timestep is necessarily known. This data comes from Johns Hopkins University's turbulent channel flow dataset. To validate the experimental data, a certain flow should be set up to be tested against existing work. Common examples include vortex rings and fluid jets. Additional issues are expected from the experimental data, such as hardware issues, calibration issues, optical issues such as noise and particles not behaving like perfect spheres.

From these tests, important metrics can be tested against other methods of flow diagnostics to determine if this method of adding information through colour is truely effective.

2.1 GANTT chart at project plan



Name	Begin date	End date
Literature review	09/10/2023	19/04/2024
Review code	09/10/2023	06/11/2023
Extend code to add colour spill	23/10/2023	29/11/2023
Work on cleaning up spill	30/10/2023	06/12/2023
Finish up last bits of code	06/12/2023	03/01/2024
analysis of real colour spill	06/11/2023	04/12/2023
Write interim review	06/10/2023	25/10/2023
Particle tracking code	25/10/2023	12/12/2023
Document code changes	24/11/2023	11/01/2024
Gather experimental data	29/01/2024	06/03/2024
Test experimental data	08/02/2024	07/03/2024
Write PPP	12/10/2023	17/10/2023
Project plan presentation	18/10/2023	18/10/2023
Interim review	08/12/2023	08/12/2023
Finalise draft report	04/03/2024	25/03/2024
table of contents for draft report	01/02/2024	01/02/2024
refine draft report	10/04/2024	01/05/2024
draft report	25/03/2024	25/03/2024
Final report	03/05/2024	03/05/2024
poster	01/03/2024	07/06/2024
Poster presentation	07/06/2024	07/06/2024

Figure 1: The original GANTT chart, as of the project plan presentation

The GANTT chart visible in 2.1 was made for the Project Plan. Since then, I have fallen behind schedule on the practical work. Because the Christmas holidays have nothing specified, this will allow me to catch up to where I wanted to be, which is ready to begin experimental work. I expect to have similar unexpected pressures on my time, leading to being behind where I want to be. For this reason, there is time allowed within each section so that the report and poster will be ready for the deadline.

2.2 Current GANTT chart

Figure 2.2 reflects the fact that I had a higher workload than I anticipated throughout the semester. I left the Christmas holidays free in anticipation of some delays, and this is why.

2.3 Gigatrack

As of now, my work with Gigatrack has been less productive than I hoped. I am able to generate synthetic data and then track the particles, however I have not make progress on changing the Optical Transfer Function yet. This is a key step in enabling me to perform the experimental work. Thankfully, the work on Gigatrack is able to be completed fully remotely. As well as the work on Gigatrack, a lot of work has been done on background reading to enable me to know the best way to work on the codebase.

Over the Christmas break, I will work on developing my colour spill tools for Gigatrack. This will mean analyzing the colour spill, using the same method as given in [5], determining the transfer function, simulating its effects, and removing the colour spill. To ensure that the transfer functions that are determined are roughly correct, the range of magnitudes of the polynomial coefficients can be compared to those in [5]. Completing this work by the start of the next semester is essential, as it means that the experimental data can be tested as soon as it is captured. This

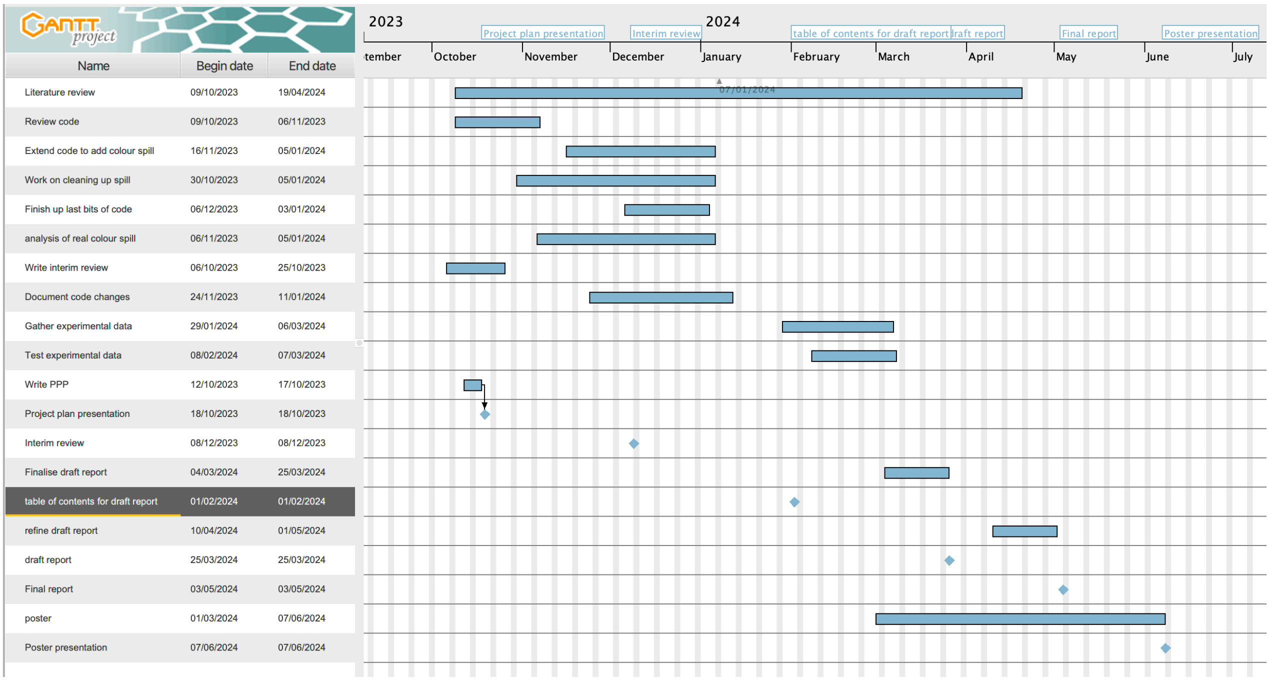


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Figure 2: The GANTT chart as of early December

allows me to iterate on my experimental methods straight away, which will be essential to completing my project on time.

References

[1] A. A. Aguirre-Pablo, M. K. Alarfaj, E. Q. Li, J. F. Hernández-Sánchez, and S. T. Thoroddsen. Tomographic particle image velocimetry using smartphones and colored shadows. *Scientific Reports*, 7(1):3714, 2017.

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[4] D. Schanz, S. Gesemann, and A. Schröder. Shake-the-box: Lagrangian particle tracking at high particle image densities. *Experiments in Fluids*, 57(5):70, 2016.

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