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Developing an Accurate Motion Estimation Algorithm within the Field of Cardiovascular Image Processing

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27th April 2017

ACKNOWLEDGEMENTS

The author would like to take this opportunity to thank the School of Computer Science and the University of Lincoln I.T. technicians for the incredibly flexible accessibility to University facilities which proved to be a valuable asset towards the completion of this project, such as the 24/7 accessibility of the University of Lincoln computer laboratories and the library.

However, the author would also like to take this opportunity to provide a significant mention to the project supervisor, Dr. Massoud Zolgharni, for the extensive support and guidance provided throughout this project. The consistent feedback and encouragement supplied was inspirational, I am sincerely grateful for your supervision and thank you for the dedication and enthusiasm towards the successful completion of this project.

ABSTRACT

The following thesis reviews the development of a motion estimation algorithm which could be applied within the field of cardiovascular image processing, this is effectively accomplished by utilising a speckle tracking technique in combination with a block matching motion estimation algorithm. This algorithm was then applied a data collection comprising of different examples of cardiovascular patient data, whereby the motion estimation algorithm's capability was established based on an average velocity plot which described the average velocity of the motion that was detected between frames of the ultrasound image throughout the entire cardiac cycle. It is hoped that this project will produce useful analytical data which can be used by clinicians with the diagnosis and prognosis of patients with cardiovascular related concerns. Overall, the outcome of this project concluded with the motion of the cardiomyocytes being detected and tracked effectively, though it should be noted that the developed solution still includes an amount of noisy motion vectors being unnecessarily tracked resulting in a slightly more obscured outcome.

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND TO THE PROJECT

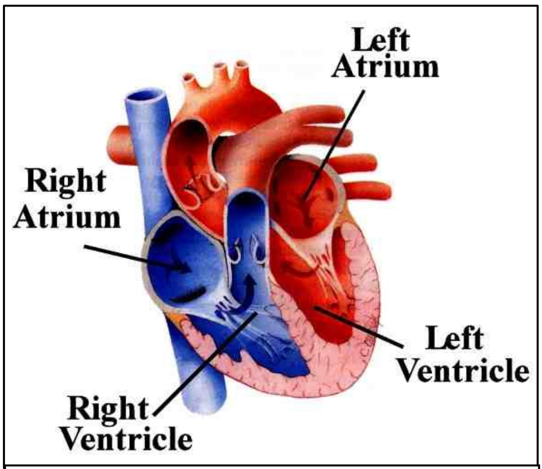

Figure 1. Image illustrating the four chambers within a human heart.

Within the medical image processing study area, an issue of paramount importance is the necessity of fast and accurate analytical data which can be derived from patient data, for the purposes of this project an area of study selected was the development of a motion estimation algorithm which could be designed to estimate the average velocity of the cardiovascular muscle movement between frames of an ultrasound image. As such, the implications of this statistical analysis are the need for accurate cardiovascular image processing techniques, such that the average velocity estimation needs be calculated as accurately as possible without the burden of unnecessary expenditure of efficiency.

Previous research in this area of study indicates that techniques such as speckle-tracking echocardiography may be used to monitor the displacement of speckles representing the myocardium, research also suggested it could be used for the strain measurement of the longitudinal, circumferential and the radial of the myocardial function during the cardiac cycle (Pavlopoulos et al., 2007). In addition to this, similar research papers investigating the analysis of ultrasound images suggest that the clinical efficacy of the algorithmic calculation for the muscle movement of the heart during the cardiac cycle is largely dependent on how accurate the block-matching motion estimation algorithm operates (Mondillo et al., 2011). The algorithm in question was required to be an accurate motion estimation algorithm capable of tracking possible subtle discrepancies between consecutive frames of a cardiovascular ultrasound image, such that small details such as the cardiomyocytes within the ultrasound image could be used as a representative for the overall cardiovascular motion between consecutive frames of ultrasound images.

In conclusion, the motivation of this project was to develop motion estimation algorithm that could be considered as appropriate for clinical application within the field of cardiovascular image processing, such that the analytical motion data obtained through this algorithm could be used to accurately estimate the average velocity during the entire cardiac cycle.

1.2 PROJECT AIM AND OBJECTIVES

Predominantly, the aim of this project was to investigate and produce an accurate motion estimation algorithm that would be capable of analysing ultrasound images for patients that suffer with cardiac-related illnesses.

This algorithm will be quantifying the speckle-pattern data that represents any movement from the myocardium during the cardiac cycle, the data of which will be used to calculate the average velocity of the muscle movement and provide additional data that can be used to help to further diagnosis or prognosis of a patient in a time efficient manner.

Explained below are the objectives, which upon completion, will help to accomplish this aim:

1. Develop a solution which is capable of performing various algorithmic operations on images in a DICOM image format, which is the format that will be used for the supplied ultrasound images.
2. Develop a motion estimation algorithm that is capable of identifying unique regions within an ultrasound image, which subsequently could be accurately tracked for any subtle discrepancies between frames of an ultrasound image.
3. Develop a motion estimation algorithm that is capable of estimating motion vectors based on the displacements of uniquely identified regions in each ultrasound image.
4. Develop the motion estimation algorithm such that the motion vector data can be used to accurately estimate an average velocity metric for any cardiovascular movement during the entire cardiac cycle.
5. Develop a motion estimation algorithm that would be compatible with any ultrasound patient data that may be used for diagnosis or prognosis by clinicians, so the developed algorithm needs to account for any differing qualities that some of the ultrasound images may have when tracking the speckle patterns reflected from the myocardium and cardio-myocytes, for example the brightness setting may be slightly different.

6. Rigorously test the motion estimation algorithm to ensure clinical applicability of the developed algorithm.
7. STRETCH objective: develop a motion estimation algorithm under a parallel programming architecture with a GPU device as opposed to a serial programming architecture using just the CPU device.

However, it became apparent later in the project lifecycle that further considerations needed to be enforced to ensure the accuracy of the motion estimations, specifically due to the fact that it was discovered later in the project lifecycle that the ultrasound images could be considered as containing an amount of noise in image, such that it was causing an element of abnormality and inaccuracy with the motion vector estimations and average velocity calculations. As such, the following objective was amended towards the completion of the project aim:

- Develop a solution which is capable of segmenting the necessary speckle pattern data away from the unnecessary noisy speckle pattern data that is apparent in most frames of the ultrasound images, such as the background speckle patterns being reflected from the myocardium.

CHAPTER 2: LITERATURE REVIEW

2.1 CARDIOVASCULAR IMAGE PROCESSING

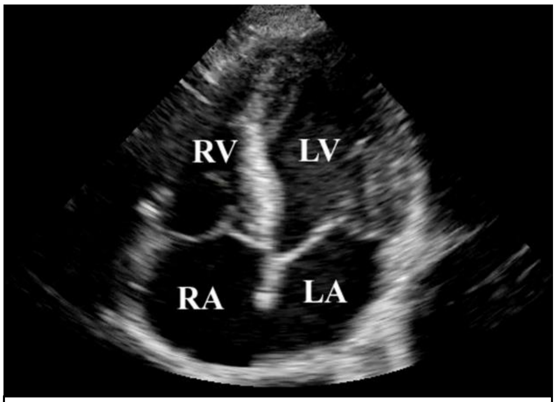

Figure 2. Image illustrating the four chambers of a human heart as an ultrasound image

Ultrasound is a medical imaging modality suited for many applications as the image acquisition is real-time, thus it is commonly utilised for surgical applications such as cardiovascular diagnosis as it is capable of offering a light, inexpensive, non-ionizing method to image the surgical field and quickly update the pre-operative planning. To this end, Fontes et al (2011) also argues that the methodology of processing the ultrasound image must subsequently be capable of accurate real-time processing, as it can be observed to be a crucial aspect within a clinical application such as cardiovascular image processing.

Rosenzweig et al (2011) explores the possible implications of using parallel processing for an ultrasound image by processing an image and comparing the capabilities of using only the CPU and using both the graphics processing unit (GPU) and the central processing unit (CPU) to process an acoustic radiation force impulse (ARFI) image, monitoring any small displacements that may have been caused within the muscle tissue. As a result of this study, Rosenzweig et al (2011) argue that the time required for processing the data was significantly reduced when the image was parallel processed using both the GPU and the CPU as opposed to serial processing with just the CPU.

In a similar study, Massanes et al (2011) suggest that current applications that require real-time motion estimation algorithms often use parallel designs for very large scale integration (VLSI) devices, but are usually costly, difficult and time consuming to develop. This study evaluates the block matching motion estimation algorithm with a full search on the frames of a surveillance video of 720 x 480 pixel resolution at 30 frames per second, under both a serial programming architecture and a parallel programming architecture. At the outcome of the project, Massanes et al (2011) argue that an implementation of the block matching motion estimation algorithm with multiple GPU cards provided a significant speedup in comparison to the speed of the algorithm when implemented with the CPU, with the speedup being improved by several orders of magnitude.

2.2 SPECKLE TRACKING ECHOCARDIOGRAPHY

One critical aspect of the proposed project is to establish a solution which is capable of identifying new locations for specific features within an ultrasound image as accurate and precisely as possible, for example the new location which the cardiomyocytes may have expanded or contracted during the cardiac cycle. Static B-scan ultrasound images, such as the DICOM images involved for this study, can be utilised in such a way that the speckles tracked on a frame of an ultrasound image can be used to describe details and features of an object contained within the image, for example any speckle patterns that may be reflecting from the myocardium or the cardiomyocytes.

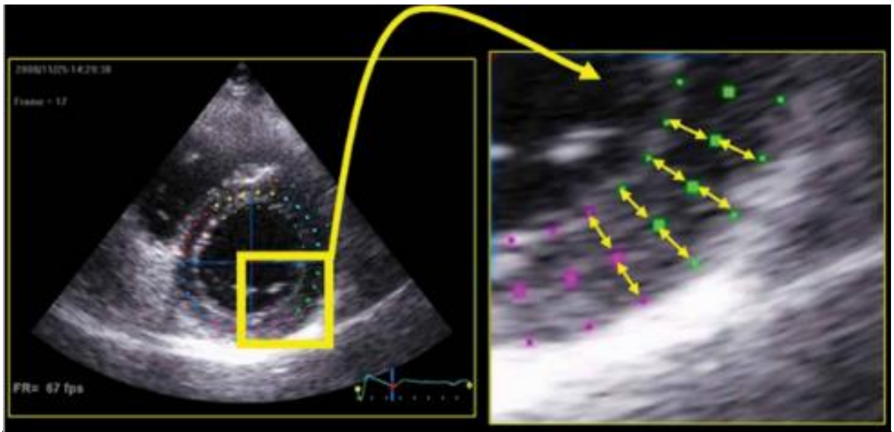

Figure 3. Image demonstrating the use of identifying unique speckle patterns and plotting motion vectors between frames of an ultrasound image (Mondillo et al, 2011).

Mondillo et al (2011) advocates that speckle tracking is a technique is fundamentally based on the analysis of speckles during the cardiac cycle, whereby single speckles are merged into functional units, in this case kernels, which can be argued to be representative of the peculiar displacement of the speckles between two frames of a sequence of images. To this end, it is argued that each kernel could constitute as a unique ultrasound fingerprint which could be tracked and quantified between each frame of the ultrasound image throughout the entire cardiac cycle, whereby Mondillo et al (2011) argues that the motion of the speckles could be estimated by comparing kernels between two frames of the ultrasound image. The motion data estimated would subsequently provide a means for providing in-depth cardiovascular analysis such as the displacement, displacement velocity, strain and the strain rate of the selected myocardial segments and left ventricle rotation.

While it could be argued that this speckle tracking technique is more subjective to data distortion than the Doppler-tissue imaging approach, speckle tracking with a high-quality ultrasound image can enable the shallower segments of the heart to be tracked more accurately. Pavlopoulos et al (2009) claim that this is largely due to the fact that the utilisation of B-mode ultrasound images uses the reflected ultrasound waves from the tissue as a result of interference by numerous reflected wavelets from the inhomogeneous medium, whereby the interference can be described as resulting in bright and dark pixels being composed in the B-mode ultrasound image, this interference pattern remains relatively constant for any small region in the myocardium which can be used as a unique speckle pattern for detecting speckle displacements in the ultrasound image.

Similarly, Notomi et al (2005) investigates the accuracy and consistency of utilising two-dimensional speckle tracking in the ultrasound images to establish a rotational velocity from the left ventricular torsion in comparison to an alternative Doppler-tissue imaging approach. The motivation behind this particular study was to investigate a possibly more effective methodology for assessing the myofibers in regards to the overall cardiac performance, whereby it was hypothesised that the speckle tracking technique could be more suitable due this approach not being as angle-dependant in comparison to the Doppler-tissue imaging approach. This study concluded that the results accomplished with the speckle-tracking technique were similar to those accomplished with the Doppler-tissue imaging approach, thus providing a potentially more clinically applicable methodology for cardiovascular image processing. On the other hand, a shortcoming of the speckle tracking echography technique that was noted was that patients who may have abnormal decorrelation scores could lead to an inaccurate representation of the left ventricular torsion movement, which therefore could lead to less reliable results being produced with the speckle tracking imaging technique (Notomi et al., 2005).

2.3 BLOCK-MATCHING MOTION ESTIMATION ALGORITHM

Another significant aspect of this project is the consideration of the approach in which the speckles are tracked between frames of an ultrasound image, furthermore the strategy which is undertaken for comparing and establishing the new location of a speckle. Effectively, a block-matching algorithm usually operates by dividing the pixels representing a particular frame in a sequence of images in a series of equally sized macroblocks, the algorithm then iterates through each pixel within the image and compares each macroblock of pixels with candidate macroblocks in a subsequent frame in a sequence of images using a similarity criterion. At the outcome of this algorithm, the resulting output should present an accurate depiction of the new location of a particular pixel which the algorithm believes the pixel may have traversed to, subsequently providing an estimate of the total displacement for each pixel which can be used to describe the overall motion between two frames in a sequence of images.

An effective and efficient motion estimation algorithm can be considered as a vital module in other fields of study and applications, for example a motion estimation algorithm could be argued to be the most important module in a typical video encoder. Huang et al (2006) seeks to further explore and compare the extensive possibilities for motion estimation techniques for video sequences and proposes that the key aspects of fast algorithms can be classified into a total of six different categories: reduction in search positions, simplification of matching criterion, bitwidth reduction, predictive search, hierarchical search and a fast full search. As such, this study proposes that the sum of absolute differences (SAD) matching criterion regards all of the pixels in the current block and a candidate block, however Huang et al (2006) proposed that the computational effort of this comparison could be reduced by performing a subsampling scheme, whereby only every second pixel within the macroblock is considered for displacement estimation in both the horizontal and vertical directions. Overall, this study claims to have yielded a speedup of approximately a factor of four while still estimating the motion with minimal error.

However, in a study surveying possible approaches for estimating the image velocity in ultrasound image sequences, Boukerroui et al (2003) investigate possible implementations for a block-matching motion estimation algorithm and compares possible similarity measures which would be utilised when comparing each of the macroblocks. In this study, a Singh block matching approach operates such that the velocity estimation is calculated based upon the only the component of velocity normal to intensity edges on the image, however it is argued that this approach loses an amount of accuracy in the calculation if the search region of the algorithm is discrete. In contrast, this study proposed that a more reliable estimate for the velocity could be calculated by using a smoothness constraint and an appropriate confidence measure. In summary, Boukerroui et al (2003) claim that the velocity at each pixel is unlikely to be completely independent of the velocity of its neighbours, and as such the velocity of each pixel could be refined based on the velocity values of the neighbourhood of velocity values.

2.4 SIMILARITY CRITERION

A key objective involved within this project is the determination of the most likely new location of a kernel in the subsequent frame of the ultrasound image, thus effectively depicting a value of displacement for each individual kernel of the ultrasound image. Ulysses and Conci (2010) investigate a total of several different approaches for establishing a potentially effective similarity criterion which could be utilised as a means for performing image registration on magnetic resonance (MR) images, where each MR image was subtly transformed between each experiment.

Overall, it was found that the SSD, MAD and SAD all produced similar, satisfactory results in regards to the calculated mean squared error (MSE), correlation coefficient (CC) and peak signal noise ratio (PSNR) accuracy values for each similarity criterion. As such, Ulysses and Conci (2010) claim that although there are few related studies which involve the SAD and MAD similarity criterions, they are capable of producing similar detection results to the SSD similarity criterion when applied with images with the same modality.

CHAPTER 3: METHODOLOGY

The following section will be discussing the methodological approach undertaken during this project in regards to the logical strategies employed throughout the entire project lifecycle to ensure the completion of the defined project aim and objectives, specifically entailing the strategies employed regarding the overall project management, requirements capture and the research methods utilised.

3.1 PROJECT MANAGEMENT METHODOLOGY

As previously discussed, the intended outcome of this project is to deliver a velocity estimation algorithm that would be suitable for integration within the application of cardiovascular image processing, whereby doctors and surgeons may be able to use the data obtained from proposed solution to help with the diagnosis or prognosis of a patient.

3.1.1 PROJECT PLAN

The time and task management of the project was pre-planned in the form of a project plan framework referred to as a Gantt chart, Wilson (2003) argues that Gantt charts provide an effective means for displaying important information and useful for implementing interactive approaches to scheduling in a project.

Effectively, the Gantt chart for this project was designed to outline a schedule for the deliverables of the project, allocating an amount of time for key tasks involved during the development under a one-week granularity. This Gantt chart was designed in reference to the preliminary risk assessment and contingency plans (see appendix B) that were undertaken, allocating a higher proportion of time towards tasks which could be considered as a higher risk of failure in comparison to other tasks of the project (see appendix A).

3.1.2 SOFTWARE ENGINEERING METHODOLOGY

There are many possible approaches which could have been chosen as the methodology for the management of this project, however the methodological approach which is selected must be justifiably robust and capable of delivering a high-quality solution at the outcome of the project. To ensure that the solution is developed efficiently, the following section will be exploring various software development methodologies and how they could potentially be integrated into the management of this particular project as well as discussing the chosen methodological approach for this project.

One possible methodological approach would be to manage the project using agile management, this approach advocates developing the solution in multiple small development lifecycles, subsequently delivering the solution in small increments as delivering one final solution at the outcome of the project in comparison other methodologies. To this end, this approach enables a methodological approach which is justifiably flexible and adaptable to change during the project lifecycle, as a project using this methodological approach could possibly develop, evaluate and iterate through a project lifecycle until a desirable outcome of the project is achieved.

On the other hand, a limitation of this advantage is the potential issue of excessive expenditure of project resources, namely allocation of project time, which would become an increasingly more prominent issue as a result of the iterative project lifecycles.

Another possible approach for managing the project would be a Waterfall methodology, this largely operates by designing the development model for the project as a single cycle of development processes which are inferred from a set of unmodifiable requirements that are specified by the client at the start of the project. However, a significant disadvantage for the inclusion of this type of model is that it introduces a high amount of risk and uncertainty into the project plan, this primarily being the difficulty and limitation of regressing to previous stages of the project to make some form of improvement or amendment. As a consequence, key features such as the block-matching motion estimation algorithm would not be able to be tested until the later stages of the project lifecycle and would leave less opportunity for the solution to be improved, this could imply possible issues with the effectiveness and efficiency of the developed motion estimation algorithm if it hasn’t been rigorously tested and consequently consistently improved throughout the entire project lifecycle. Thus, it could be argued that this in turn would imply that a significantly less robust and lower quality solution to be developed in comparison to other software engineering models.

In conclusion, it should be noted that as this project is an individual project, many of the discussed benefits from some of the software engineering methodologies will be limited by the fact that some aspects of the project are unable to take advantage of multiple team members contributing to the project, however the software engineering methodological approach selected for this project was a theoretical methodological which was largely inspired by the agile methodological approach.

A fundamental aspect of this project is to be able to deliver a real-time, accurate motion estimation algorithm capable of estimating cardiovascular motion within an ultrasound image, as such the methodological principles followed during this project were those adhered from the agile approach, whereby the project lifecycle would be largely executed through the use of small, consecutive software development lifecycles. While it can be argued that inspiration from the waterfall methodology would advocate the concept of delivering the project in a potentially more timely manner as the solution would not need to be consistently tested at various stages of the project, the selected approach ensures that the solution delivered at the outcome of the project will be rigorously tested and capable of providing meaningful and effective data in later stages of the project.

To adhere to some of the principles of the agile philosophy, each version of solution would be tested using black-box and white-box testing approaches at the completion of each iteration of the project lifecycle, this allowed opportunity for the current version of the solution to be reviewed which could be subsequently acted upon in the next iteration of the project lifecycle. For example, during milestone two of the project plan, it was established that the current version of block-matching motion estimation algorithm was not achieving the intended results and was subsequently incorrectly estimating the motion present within the ultrasound image. This can be considered as a significant issue in the project, as the quality of the block-matching motion estimation algorithm is at the core of the solution which would negatively affect the final results if ignored. However, an agile approach to this project allowed the issue to be methodologically managed at the start of the subsequent project lifecycle iteration by adapting the plan and requirements of that iteration, whereas in comparison this improvement would be difficult for inclusion with a waterfall methodology. This in turn allowed the project to deliver a thoroughly improved solution as a consequence which would be capable of producing more significant and accurate data which could be used as a representative of the velocity of the heart muscle contraction and expansion between frames of the ultrasound image.

3.2 REQUIREMENTS CAPTURE

To develop a solution which would be capable of accomplishing the pre-determined aim and objectives of this project (see chapter 1.2), an understanding of the user requirements can be considered as a paramount factor in the design of solution which would determine the clinical applicability of the final outcome achieved through this project. To this end, each prototype that was developed through the course of this project was periodically evaluated by clinicians through the deployment of a trial application each prototype, whereby immediate feedback could be supplied for the establishment of further improvements which could be made to the existing prototype of the algorithm in the interest of clinical applicability of the motion estimation algorithm.

Regular communication to clinicians was established through the aid of the project supervisor, Dr. Massoud Zolgharni, who was able to maintain close contact with various clinicians on a daily basis.

3.3 RESEARCH METHODOLOGY

As previously elaborated, the fundamental aim of this project was to develop an accurate motion estimation algorithm that provides the necessary capabilities for integration within the application of cardiovascular image processing (see chapter 1.2), whereby the proposed solution could arguably provide clinicians with further means of diagnosis and prognosis of patients with cardiovascular concerns. The outcome of this project aims to help contribute towards providing more accurate analytical data which could arguably be considered as more representative of a patient's health condition when regarding the cardiovascular diagnosis or prognosis.

This data will be quantitative data which can be examined and statistically analysed in regards to elapsed time and its ability to estimate appropriate velocity values for the muscle movement present between frames of an ultrasound image in real-time, these results will be plotted in the form of velocity plot over the entire cardiac cycle recorded in each example cardiovascular ultrasound image that was provided. These results will then be compared between each patient to assess the effectiveness and efficiency of the solution's ability to deliver towards the objectives and aim of the project (see chapter 1.2).

CHAPTER 4: SOFTWARE DEVELOPMENT LIFECYCLE

The following section will entail a more in-depth discussion regarding how the project was managed at prominent stages of the project lifecycle, further exploring what software development processes were employed and their desired impact on the overall management and delivery of the project.

4.1 DESIGN

As previously discussed, the intention behind the completion of this project was to employ an accurate and reliable motion estimation algorithm which would be capable of estimating the velocity of the cardiomyocytes within an ultrasound image as the myocardium contracts and expands during the cardiac cycle, as such an imperative characteristic to be noted in order to accomplish this is to ensure that the solution is capable of determining the motion of speckles within the ultrasound image in real time. The following section will be exploring the fundamental design processes employed throughout the design stage of the software development lifecycle of this project, specifically entailing how the solution was tailored towards accommodating the previously discussed aim and objectives of this project.

4.1.1 BLOCK-MATCHING MOTION ESTIMATION ALGORITHM

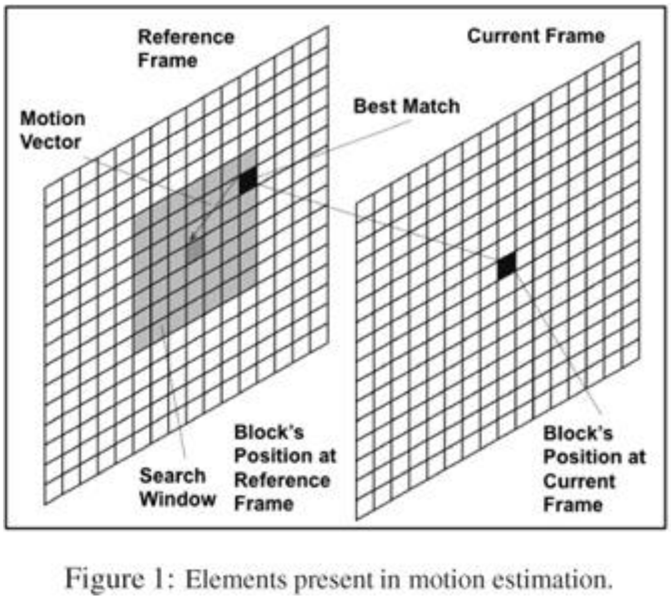

Figure x . …… (http://www.scielo.br/scielo.php?script=sci_arttext&pid=S2179-84512014000100010)

One fundamental problem which was required to be solved for this project was to establish a means for accurately depicting the amount of movement that may have occurred between two frames of the ultrasound image, to inherently establish a value which can be argued to be representative of the total distance the cardiomyocytes contracted between frames of the ultrasound image. As such, research undertaken within the literature review of this project indicated that one approach for accomplishing such an objective would be to implement a search algorithm in the form of a block-matching motion estimation algorithm in combination with the speckle tracking technique.

In a recent study (Mondillo et al, 2011) suggests that speckle patterns observed in an image can be used as a representative as an identifier of different features within the image, and in turn was proposed that these speckle patterns could be utilised as a comparator between two frames of an image. To this end, this project utilises a technique referred to as a block-matching algorithm which is used for measuring the similarity between two similar images or segments of images in regards the pixel data (Shi and Sun, 2000).

This algorithm operates by iterating through each pixel within a frame of the ultrasound image at a pre-defined step size, whereby the speckle pattern of each pixel is established by the neighbourhood of pixels surrounding the currently selected pixel, effectively forming a macro block of pixels. This macro block of pixels is then loaded into a kernel matrix and compared with the macro blocks of pixels in the subsequent frame of the ultrasound image, searching through all macro blocks within a defined search window (see chapter 4.1.2) and comparing against each one to establish which macro block in the subsequent frame is justifiably the most similar to the currently selected macro block from the original frame of the ultrasound image through the use of a similarity criterion (see chapter 4.1.3). As claimed by Boukerroui et al (2003), the velocity at each pixel is unlikely to be completely independent of the velocity of its neighbours, so the velocity of each pixel is refined based on the velocity values of the neighbourhood of velocity values to produce a more resourceful outcome for the motion estimation.

4.1.2 SEARCH STRATEGY

As previously discussed, a fundamental part of the design for the block-matching motion estimation algorithm was the consideration for search strategy, specifically in regards to search window inferred when searching through a frame of the ultrasound image for most similar macro block in the subsequent frame of the ultrasound image in respect to the currently selected macro block of pixels from the original frame. As such, the search strategy that will be enforced for this particular project will be the utilisation of a fast search technique, whereby the number of candidate macro blocks which the block matching motion estimation algorithm will be comparing will be significantly lower than the total of candidate macro blocks that would be apparent through the full search technique. In respect to this particular project, a focus within the project aim is to accomplish a block-matching motion estimation algorithm that is capable of real-time processing a cardiovascular image in the format of an ultrasound image, as such a fast search technique will compress the search window to a smaller area of pixels surrounding the selected pixel from the original frame, thus enabling a much more efficient result to be obtained.

4.1.3 SIMILARITY CRITERION

To enable the comparison, a kernel is established which embodies the concept of taking the currently selected pixel and its neighbours from a frame of the ultrasound image and using it as a reference kernel when searching and comparing this kernel with multiple kernels within a search window of the subsequent frame of the ultrasound image, attempting to locate the kernel which can be argued to be the most likely new location of the currently selected kernel.

However, an issue of vital importance that was presented was how the algorithm could determine which kernel within the search window could be characterised as being the most similar, and incidentally the most viable, kernel in regards to the currently selected reference kernel. The implications of this decision made by the algorithm being that it will determine the accuracy and reliability of the final velocity value output estimated between two frames of the ultrasound image, hence a sum of absolute differences (SAD) metric was calculated between the currently selected reference kernel and a kernel within the search window of the block-matching motion estimation algorithm.

4.1.4 NOISE REMOVAL

One objective of this project which could be considered as a key asset for the aim of the project to be fulfilled was the consideration of noisy pixels which are inherently present throughout all of the ultrasound images.

The noise present in the ultrasound images was conducted in a total of two different ways, the first being through the application of an image segmentation technique. For the purposes of this project, the only pixels that need to be considered for the velocity estimation are pixels which are representative of the cardiomyocytes within the ultrasound image, thus the inclusion of further pixels within the velocity estimation would be unnecessary and can be considered as noise for the algorithms.

As a result, the developed solution pre-processes each frame and converts the ultrasound image to a binary image, effectively segmenting the cardiomyocytes away from the remainder of the image. The resultant binary image can then be utilised as a mask for flagging noisy motion vectors, whereby only pixels that describe the cardiomyocytes within the ultrasound image will be considered for the algorithm and flag any subsequent noisy motion vectors.

Consequently, the inclusion of noisy motion vectors, such as abnormal values as a result of the presence of noise, can subsequently lead to the output of the algorithm to be distorted and produce a significantly less accurate estimation. To counter this issue, an average motion vector value was estimated and subsequently compared with each motion vector that was observed in each region of the ultrasound image, this data was then utilised to determine which motion vector values could be considered as noisy motion vectors based on the angle difference between each motion vector and the estimated average motion vector.

This was predominantly accomplished by calculating a tangent value based on each motion vector and the estimated average motion vector, such that if the tangent value was estimated to be larger than a threshold value it would be flagged as a noisy motion vector and will be ignored in the final velocity estimation calculation. Therefore, a new vector containing Boolean values representing the flag values can then be cross-referenced used as an identification of whether a particular motion vector, if noisy, should be ignored in subsequent operations of the solution.

4.3 TESTING AND EVOLUTION

While the previous section explored the intended design of the solution, this section will be exploring how each of the originally planned features of the solution were developed and implemented into the final version of the solution. While the design stage of the project lifecycle was imperative for the initial preparation of the solution, developmental results can provide further insight in regards to how some features of the project could be adapted and improved.

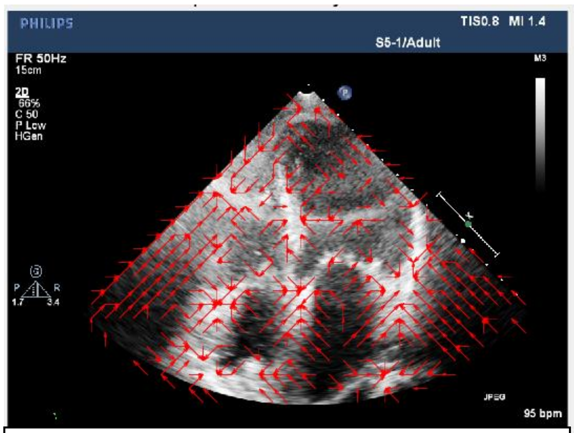

Figure 4. Motion vectors estimated on an early prototype of the motion estimation algorithm.

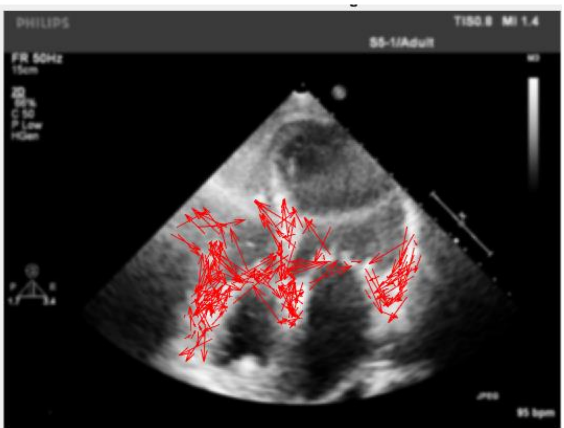

Figure 5. Motion vectors estimated on the final prototype of the motion estimation algorithm.

The original design of the block-matching motion estimation algorithm entailed optimising the solution by utilising a search strategy which depicted a strict search window surrounding the currently selected block of pixels which the algorithm could operate on, however when developing this feature during one of the agile-inspired methodological approach followed with this project, the design of this feature was adapted to opting for a full search strategy as opposed to a fast search. This change in design allowed the block-matching motion estimation algorithm to operate a more effective search technique, where it was guaranteed to find the most likely new location of a group of pixels if the search window was expanded to being the entirety of the image.

As demonstrated in figure 4, it can be observed that the motion vector displacement values could be somewhat forced values when utilising a fast search strategy for the block matching motion estimation algorithm, whereas in figure 5 it can be observed that the motion vector disc lament values are seemingly more flexible values. In summary, it can be argued that this design improvement for the solution is implemented at the cost of processing efficiency, as this version of the solution will notably require a significantly larger amount of computational resources and expenditure due to the significant increase of candidate macro block which the algorithm now has to operate on. However, this design improvement was retained in the final prototype as it was noted that a full search strategy was capable of achieving considerably more effective results for the project.

CHAPTER 5: EVALUATION

The aim and objectives of this project (see chapter 1.2) entailed not only the development of a motion estimation algorithm, but the development of such an algorithm which could be considered for application within the field of cardiovascular image processing. Thus, to establish and evaluate the effectiveness and efficiency of the developed algorithm and its possible application with the field of cardiovascular image processing, the algorithm was rigorously tested against a data collection containing authentic cardiovascular ultrasound image patient data (see chapter 3.2), whereby the effectiveness and efficiency of the algorithm would be established based on its performance on each example set of data and consequently therefore its performance within a clinical application. The following section will be determining what can be observed from the outcome of the project and its significance in regards to the original project aim and objectives.

5.1 PERFORMANCE ANALYSIS

As previously discussed, the developed motion estimation algorithm was tested on an ultrasound image data collection which comprised of a total of twelve different examples of cardiovascular ultrasound image data, whereby the robustness and flexibility of the developed solution would be tested in regards to dealing with data which may contain slightly different pixel values, for example a different brightness setting may be used between the example sets of data.

Overall, as can be observed in the results (see Appendix C), the developed solution is capable of detecting motion of speckles inherent between frames of the ultrasound, whereby the displacement of speckles which depict possible motion of the cardiomyocytes within the ultrasound image can be tracked throughout the entire cardiac cycle recorded. This in turn was successfully cross-referenced and as a consequence was capable of estimating the total velocity of the muscle movement present between consecutive frames of an ultrasound image, which was arguably successful in regards to its functionality.

To assess the solution, average and median metrics were calculated in regards to showing the average level of motion which could be detected when applying the solution to all twelve example sets of patient data, specifically by estimating the average velocity of the muscle movement based on the raw velocity values estimated for each individual motion vector depicted between frames of each example set of patient data. As a consequence, the average velocity metric plot of the solution should be comparable to realistic values that could be calculated for the muscle movement during the full cardiac cycle.

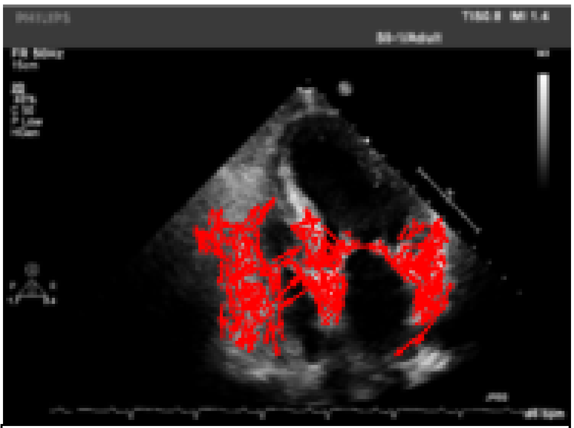

Figure 6. Motion vectors estimated on the final prototype of the motion estimation algorithm.

Overall, it can be argued that the motion estimation algorithm is capable of detecting some motion with most example sets of the patient data, whereby the motion vector plots can be observed to be capable accurately estimating most motion vectors representative of the cardiomyocytes within the ultrasound image (see figure 6), thus the correctly estimating the average velocity of the muscle movement present in the ultrasound image. For example, as the number of frames increase, it is likely that the average velocity estimation will increase and decrease as the cardiomyocytes function the muscle contraction and expansion throughout the entire cardiac cycle.

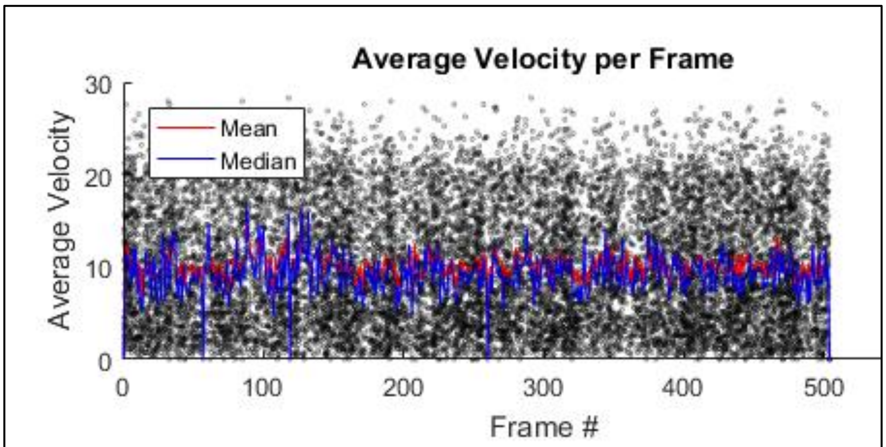

Figure 7. Estimated average velocity plot, demonstrating the impact of the inclusion of noisy vectors in the final prototype.

However, it can also be observed that the developed solution is not perfect, predominantly due to a level of noise remaining in the image and consequently distorting the estimated motion vectors and average velocity values from their true value. This can be particularly observed with the average velocity plot (see figure 7) in some segments of the plot, as the gradient between some of the frames appears to be sporadic and depicts an abnormal pattern between the data, with the values sharply increasing or decreasing between frames of the ultrasound image as the motion estimation algorithm mistakenly identifies some of the motion vectors as noise, which subsequently leads to some of the motion vectors being abnormally large, thus resulting in a sharp increase as can be observed in the figure above. It was intended for further noise removal to be experimented within this project, however due to time constraints this feature had to be discarded for other aspects of the project to be prioritised.

5.2 CONCLUSION

Overall, the outcome of this project depicts a possible implementation for a motion estimation algorithm in the form of a block-matching motion estimation algorithm which is designed for the purpose of estimating subtle speckle pattern discrepancies for cardiovascular motion that may be present within ultrasound images, to this end it can be argued that this project effectively delivered this project aim successfully, though areas of improvement in the algorithm are evident. The developed motion estimation algorithm is clearly capable of estimating an amount of motion within cardiovascular images such as ultrasound images (see figure 6), the success of which was confirmed when applying the motion estimation algorithm on the previously discussed data collection of cardiovascular ultrasound image patient data. The mean and median average metric results indicated a somewhat accurate depiction of what the cardiovascular motion between frames of each ultrasound image could be, despite abnormal noisy velocity points between some frames of the ultrasound images.

The developed motion estimation algorithm can be concluded as being capable of effectively analysing and detecting speckle displacements between consecutive frames of the ultrasound images and subsequently capable of using this data to accurate plot the overall velocity of the muscle movement present within the ultrasound images.

5.3 AREA FOR FUTURE RESEARCH

As evident from the previous discussions, areas of this project were omitted from further exploration due to time constraints and other shortcomings faced throughout the course of this project, as such segments of this project could be improved upon and experimented with further in future projects. Thus, the following section will be exploring and discussing areas of this particular project which may, upon further exploration and experimentation, yield improved results from this project.

5.3.1 ADDITIONAL NOISE REMOVAL

As previously discussed, the conclusive results from this project indicate a successfully developed motion estimation algorithm which is effectively capable of operating within the field of cardiovascular image processing, however despite all attempts within the timescale of the project an imperative issue that remained in the final prototype of the solution was the inclusion of noise within the distribution of the motion vectors.

The direct consequence of the inclusion of the remaining noisy motion vectors in the final prototype of the motion estimation algorithm is a limitation on the credibility of the accuracy and precision of the average velocity estimation, as demonstrated with the data collection containing authentic ultrasound patient data. As such, if further time could be opted for this project, further exploration would be required for the removal of more noisy motion vectors which evidently remain around and within the cardiomyocyte segmentation within the image, this would hypothetically allow a much more accurate representation of the motion within the ultrasound images which should consequently produce a much smoother average velocity estimation plot between each frame in the ultrasound image.

5.3.2 PARALLEL IMPLEMENTATION OF THE DEVELOPED SOLUTION

Research undertaken as part of the literature review (see chapter 2) indicated that an imperative characteristic for cardiovascular image processing is the operational efficiency of the image processing techniques that are being applied, particularly as the image acquisition time for ultrasound images can be considered as real-time (Fontes et al, 2011). As such, the applicability of the developed motion estimation algorithm could be explored further by ensuring that operational efficiency the motion estimation algorithm is equal to that of the image acquisition speed, allowing clinicians to operate with the data in a theoretically more efficient manner.

Thus, the implementation of this project could be explored further by considering the development of the same motion estimation algorithm under a parallel programming architecture, whereby the kernel operations could be divided between multiple GPU devices that may be installed as part of the hardware of a clinical workstation as opposed to using a single CPU device. This in turn would theoretically allow for an exponential speedup increase (Rosenzweig et al, 2011) for the motion estimation algorithmic operations that are performed on the ultrasound images, thus it could be argued to provide a potential means for achieving real-time cardiovascular image processing with a motion estimation algorithm. In conclusion, further investigation in this area of the project could enable further clinical applicability of the motion estimation algorithm.

CHAPTER 6: REFLECTIVE ANALYSIS

The following section will entail a critical reflection regarding the processes following and the efficacy of decisions made during the course of this project, specifically regarding their impact on the project and what personal lessons may have been learned as an outcome.

6.1 COMPLETING THE PROJECT

Overall, the project execution was arguably successful in regards to accomplishing most of the original objectives and therefore aim of the project, and as such the developed motion estimation algorithm was capable of estimating subtle amounts of motion that would be present within a cardiovascular ultrasound image. At the outcome of the project, it can be argued that the perceived overall difficulty for the project execution was underestimated considerably, with the project objective of estimating the motion vectors between frames of an ultrasound image as accurately as possible proving to be a laborious task. As previously discussed, this was largely due to different search strategy attempts with the motion estimation in-development continuously included amounts of noisy motion vectors, however this issue was minimised by minimised through a binary image segmentation technique to segment the cardiomyocyte objects away from the noisy background pixels in each of the ultrasound images.

6.2 DEVELOPMENT WITH MATLAB

As previously discussed, a fundamental asset towards the completion of this project was the utilisation of the development tool and programming language MATLAB. In spite of this, during early stages of development for the motion estimation algorithm, there was a heavy constraint burdening the amount of developmental progress that was being made with the project, this was largely due to an initial lack of skill and knowledge for integrating the algorithm development with the MATLAB programming language. Fortunately, this became less of an issue as the project progressed through the project lifecycle, however it can be noted that the decision to utilise a development tool of which no prior knowledge was acquired lead to inefficient, unstructured MATLAB code being initially developed which in turn lead to some of the early prototypes of the motion estimation algorithm suffering in quality because of this. As such, it could be argued that the development tools decision selected for this project could have been the selection of the C++ programming language, as it can be noted that more experience and knowledge of this programming language has been gained on a personal level in comparison to MATLAB. Despite this, the new techniques and programming language learned as a result of this project can be argued to overshadow the potential advantages of utilising C++ in development instead, development with MATLAB in later stages of the project simplified the development of some features of the motion estimation algorithm.

6.3 DEBUGGING A SERIAL IMPLEMENTATION OF THE SOLUTION

A decision made during the design stage of the project was to ensure that the motion estimation algorithm was designed under a serial programming architecture before possibly developing the same motion algorithm under a parallel programming architecture as a STRETCH objective, whereby the various kernel operations defined by the motion estimation algorithm would be procedurally executed over time as opposed to being executed concurrently. However, an implication of this design choice was a consistent issue of slow debugging particularly during the later stages of the project and made finding solutions to specific bugs present in the developed code more difficult. This was largely due to the serial implementation of the project procedurally executes the previously discussed algorithmic operations procedurally under a primary utilisation of the CPU device installed on the workstation, which has been noted to being considerably slower in similar projects which took advantage of parallelisation opportunity present with a parallel GPU device implementation of the project (Rosenzweig et al, 2011).

6.4 METHODOLOGY REFLECTION

As previously discussed, the principles of the agile methodological approach towards software engineering projects advantageously allowed the software development processes of this project to be undertaken through a series of iterations of small lifecycles. However, it can also be observed that while this methodological approach would enable a theoretically higher quality and therefore more effective solution to be solution at the outcome of the project, it can also be observed as being a shortcoming for the management of this particular project. This is largely due to the fact that the development of some features involved with the project required more development time than initially anticipated, for example more time was consistently added for the improvement of the block-matching motion estimation algorithm to ensure a high-quality solution was created, however this subsequently lead to less time being allocated for later stages of the project. In summary, as this project had a strict deadline enforced, it could be argued that the project may have benefitted from a slightly different methodological approach which was tailored more towards development speed as opposed to a quality focus, for example a waterfall methodology.

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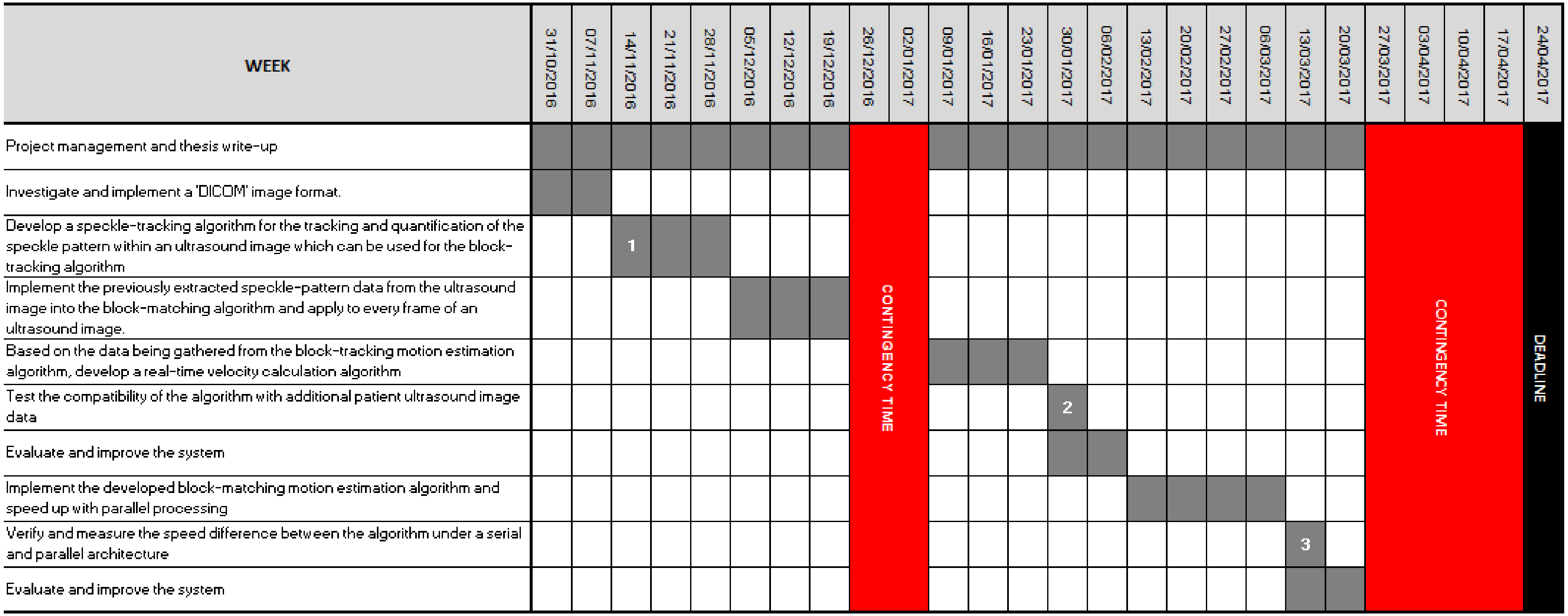
APPENDIX

APPENDIX A: GANTT CHART

Appendix A shows the Gantt chart that was designed as part of the project plan, whereby each task defined in this plan can be allocated project resources under a one-week granularity.



APPENDIX B: PRELIMINARY RISK ANALYSIS AND CONTINGENCY PLAN

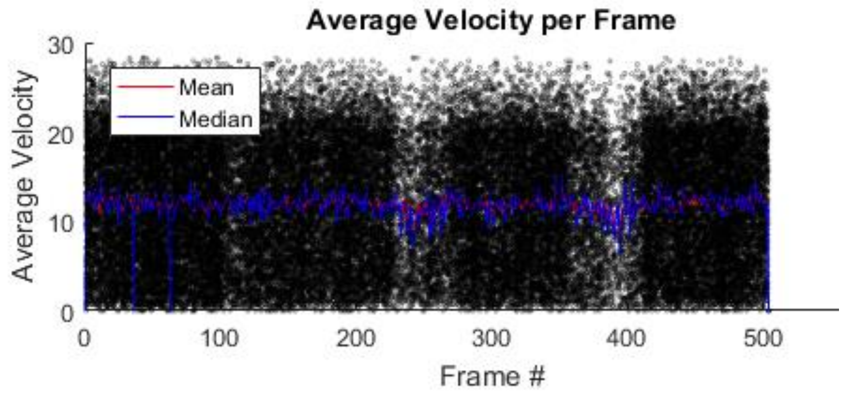
Appendix B shows a risk analysis matrix which was used to identify possible significant risks which may need to be considered during this project, nevertheless it should be noted that this analysis only prioritises risks that are specific to this particular project and will not be considering the handling of common risks such as the failure of hardware and equipment. The risk quotient has been calculated by: *impact level x risk likelihood*.

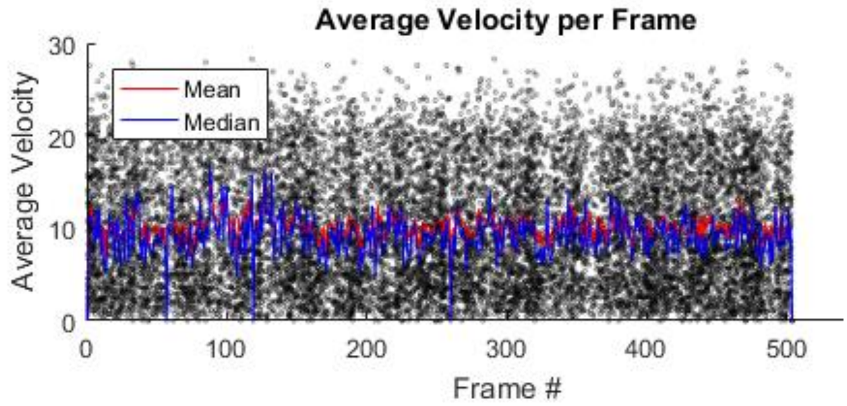
Risk Description	Risk Likelihood	Impact Level	Risk Quotient	Contingency Plan
The provided ultrasound image of the patient's heart may not load into the system as intended, which would lead to it being impossible for any velocity data to be calculated from the ultrasound image.	0.3	7	2.1	Assuming that the issue lies with the quality of the ultrasound image that was supplied, the original ultrasound image data will be securely destroyed and a request for a different copy will be made. However, this concern will be passed onto the supplier of the ultrasound image if the issue is still unresolved.
The developed object-tracking algorithm may not work on all examples of the patient data and may fail to be compatible with any subsequent DICOM images that are provided for additional patients.	0.4	6	2.4	The issue however may result from the fact that the ultrasound image was recorded from ultrasound hardware than the other DICOM images, so the amount of scan lines may be marginally different. In this case, debugging time can be saved by testing the developed algorithm on further examples of patient data and could be made compatible with the existing algorithm by managing the speckle-tracking quantification calculation to consider the potential change in scan lines and handle this particular ultrasound image separately.
The allocated time for a particular task may overrun, for example there could potentially be a delay with the development or implementation of the object-tracking algorithm. Thus, this small delay would delay later tasks and would further delay the	0.6	5	3	Contingency time will be built in within the project plan and will be utilised as additional time in the event that particular objectives for the project take a longer amount of time to complete than originally intended. As a result, this makes the likelihood of the project not being

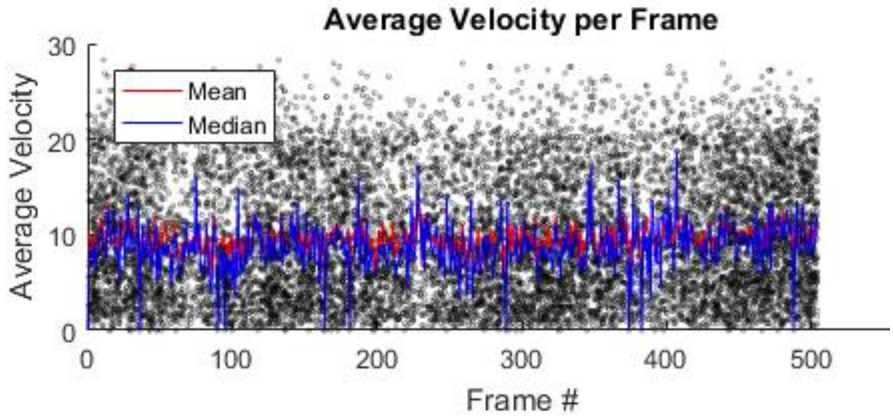
entire project, presenting the risk of not being able to complete the project for the planned deadline.				completed on-time for the intended deadline significantly less likely.
The confidentiality of the ultrasound image data from each patient may become compromised and susceptible to unauthorised access.	0.3	9	2.7	All work done for the project in regards to the patient's DICOM image will be done in a confidential workspace and will not be shared with any member of the public.
Ineffective storage could risk unauthorised access to any ultrasound image data that has been supplied by the patients.	0.3	9	2.7	The patient data will be stored securely in a password protected and encrypted zip folder on a separate external hard drive, where the naming convention for the relevant files and folders will not relate to patient's personal data.
A patient may decide to withdraw any ultrasound image data that they shared for the purposes of this research project.	0.3	8	2.1	The original ultrasound image data will be securely removed from all data storage locations and further ultrasound image data will be gathered from a different patient that will agree to the University of Lincoln ethical research guidelines.
The complexity of the developed block-matching motion estimation may be too high for it to be adapted to use parallel processing as opposed to serial processing, and may be difficult to complete within the project timescale.	0.4	7	2.8	Assuming that the allocated contingency time is not enough to accommodate the issue of converting the algorithm from using serial processing to parallel processing, the parallelisation of the algorithm is considered as a STRETCH objective and therefore may not be completed within the proposed timescale of the project. In the event of this, the production of the developed algorithm under a parallel processing architecture will be proposed for further research and this project will conclude results based on the findings discovered within the serial processing architecture.

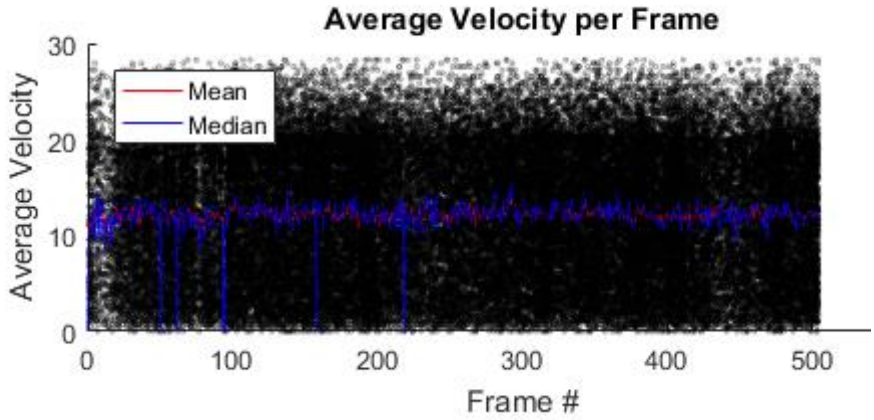
APPENDIX C: FINAL PROTOTYPE OUTPUTS

Appendix C shows the output results obtained when operating the final prototype of the developed motion estimation algorithm throughout the entire cardiac cycle tracked in each of the DICOM images that were tested.





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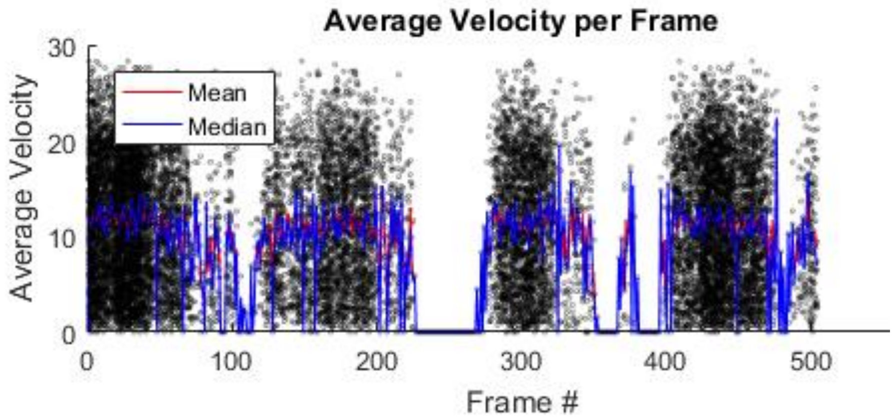
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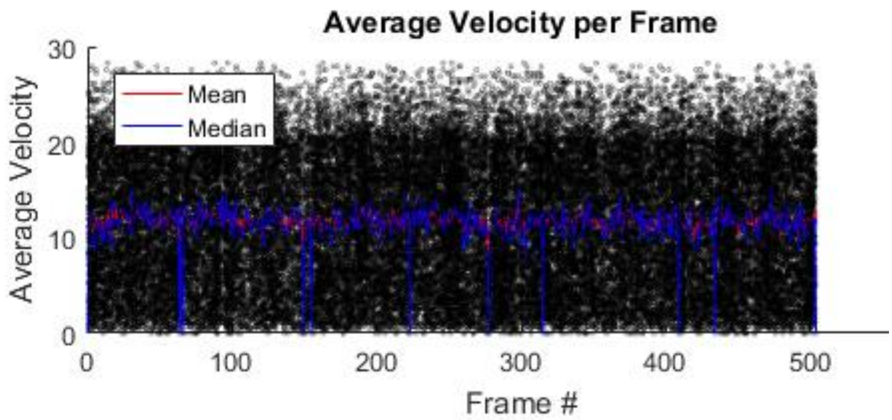
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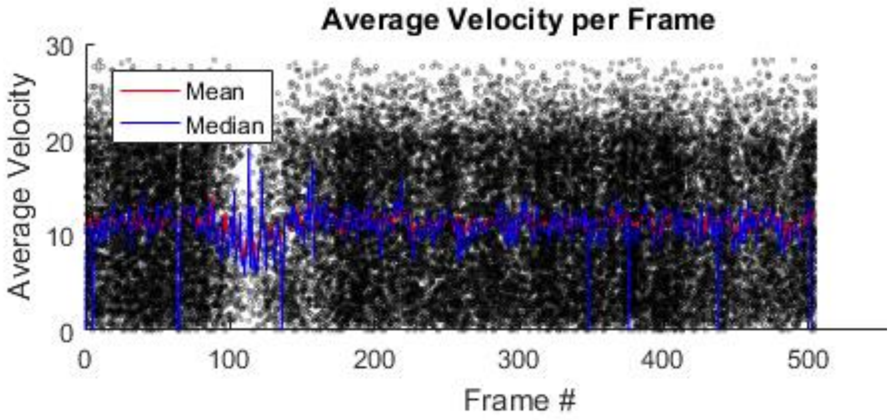
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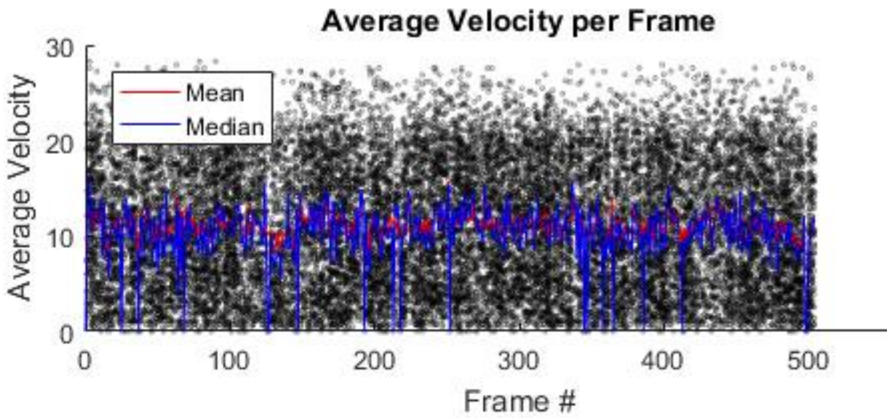
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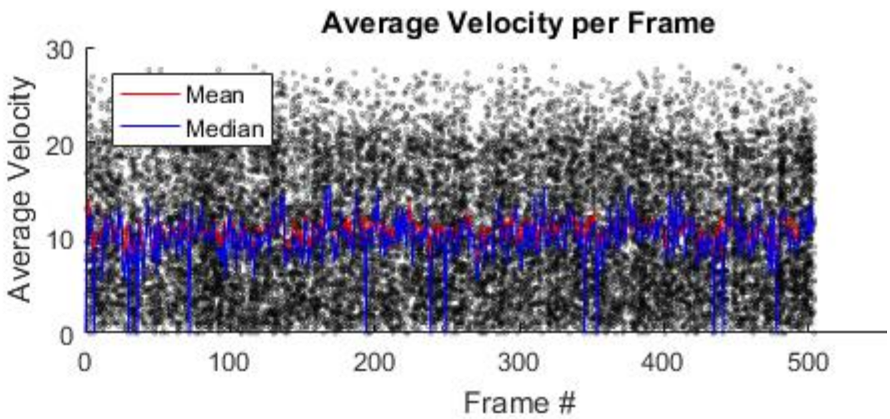
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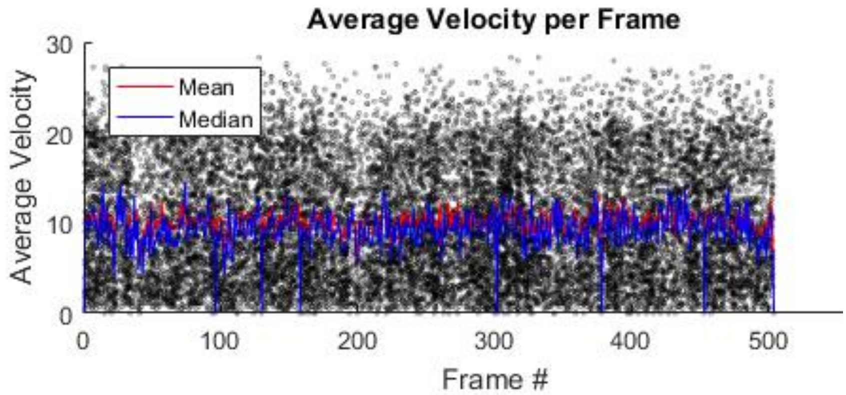
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