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UNIVERSIDAD PONTIFICIA

ICAI

GRADO EN INGENIERÍA EN TECNOLOGÍAS  
INDUSTRIALES

TRABAJO FIN DE GRADO

CALCULATION OF THE PERIPHERAL ARTERY'S  
AREA THROUGH ULTRASOUND IMAGING

Autor: Álvaro Izaguirre de Benito

Director: Kenn Oldham

Madrid

Julio de 2019

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Director: Kenn Oldham

Madrid

Julio de 2019

# **CÁLCULO DEL ÁREA DE UNA ARTERIA PERIFÉRICA A TRAVÉS DE IMÁGENES POR ULTRASONIDO**

**Autor: Izaguirre de Benito, Álvaro.**

**Director: Oldham, Kenn.**

**Entidad Colaboradora: Universidad de Michigan.**

## **RESUMEN**

### **1. Introducción**

El trabajo realizado ha consistido en estudiar, de forma no invasiva, la evolución del área de una arteria.

El estado y comportamiento de las arterias son indicadores fisiológicos esenciales; conocer estos indicadores nos permite predecir cómo puede el cuerpo responder a las enfermedades agudas y crónicas.

El tono vascular se refiere al grado de constricción de las arterias en relación con un estado en el que la arteria está completamente dilatada; puede utilizarse como un indicador de cómo responderá el cuerpo a situaciones de estrés cardiovascular (situaciones en las que no hay un comportamiento normal, como en las hemorragias). El tono vascular es uno de los factores más importantes al evaluar la resistencia vascular sistémica del cuerpo, o la resistencia que siente el corazón cuando bombea sangre a través del sistema vascular a todas las células de nuestro cuerpo. El tono vascular es uno de los mecanismos de compensación más importantes que tiene el cuerpo para mantener la homeostasis fisiológica (que se refiere a la tendencia del cuerpo a mantener los parámetros fisiológicos -como la presión arterial y la temperatura corporal- del propio cuerpo dentro de un rango específico de valores). [WANG17][PEAR12]

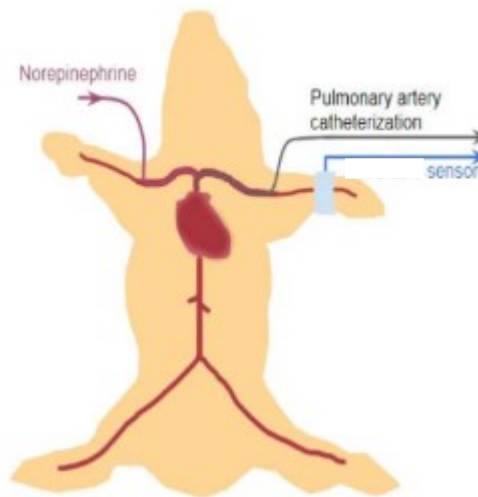
Sin embargo, determinar el tono vascular puede ser difícil utilizando las tecnologías disponibles en la actualidad, más incluso cuando el tono vascular se está

evaluando de forma no invasiva. La mayoría de las tecnologías no invasivas tienen problemas de complejidad (ya sea porque requieren de algún tipo de conocimiento o porque los instrumentos necesarios son complejos), de precisión o no proporcionan una medición continua. La solución propuesta se enfrentará a todos estos problemas.

El sensor elegido para obtener la información sobre el estado de las arterias es un dispositivo de ultrasonido. Las imágenes generadas por un dispositivo ultrasonido se basan en los mismos principios involucrados en el sonar que es utilizado por diferentes animales, como los murciélagos, para poder "ver" lo que hay a su alrededor. Cuando una onda de sonido golpea un objeto, parte de la onda de sonido rebota. Al medir estas ondas que rebotan, es posible determinar cómo de lejos está el objeto, así como el tamaño, la forma y la consistencia del objeto (ya sea que el objeto sea sólido o esté lleno de líquido). [RADI18]

Para obtener información para desarrollar la solución y verificar los resultados obtenidos, será necesario realizar un experimento con un animal. Se utilizará un cerdo para extraer toda la información requerida para este experimento. El cerdo utilizado en la prueba fue anestesiado para poder realizar las mediciones cardiovasculares, las maniobras realizadas están sujetas al protocolo animal PRO00006553 de la Universidad de Michigan. La presión arterial media y el flujo cardíaco se rastrearon de forma invasiva mediante cateterización de la arteria pulmonar. El sensor de ultrasonido se colocó en una de las extremidades del cerdo, obteniendo así una imagen de una sección transversal de la arteria radial. Para inducir cambios en la resistencia vascular sistémica, se utilizaron infusiones periódicas de norepinefrina. La norepinefrina produce vasoconstricción (estrechamiento de los vasos sanguíneos), concretamente de los vasos sanguíneos pequeños, lo que aumenta la presión arterial. [WANG18]

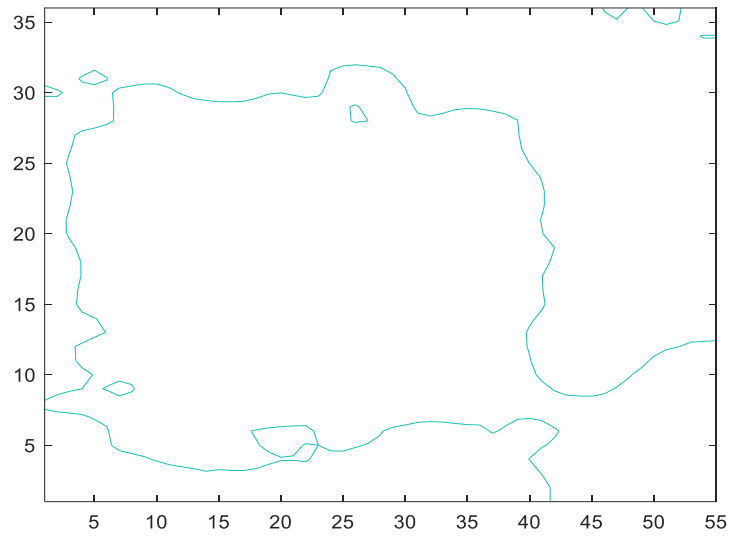




*Ilustración 1: Disposición del cerdo y sensores en el experimento [WANG18]*

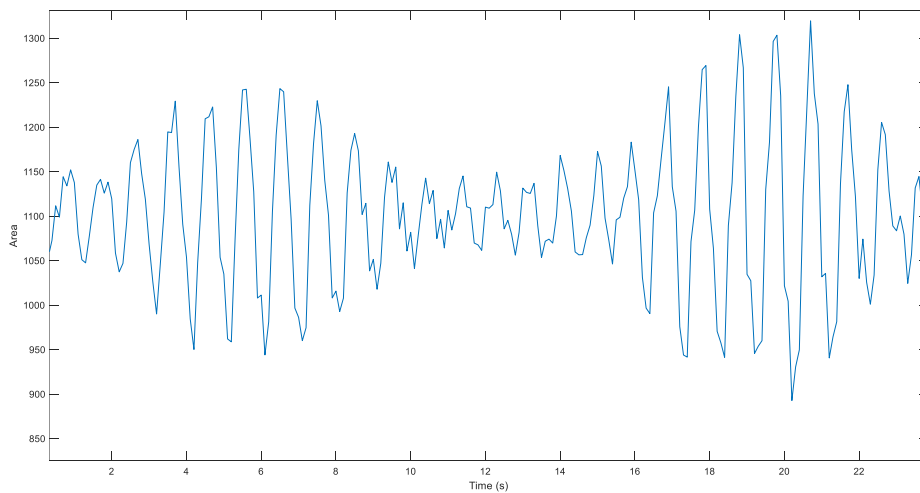
## 2. Planteamiento

El tono vascular se puede medir mediante el cálculo del área de las arterias. Para ello, mediante el sensor de ultrasonidos se han obtenido vídeos de la evolución del tamaño de la arteria. El método utilizado para calcular el área se basa en cómo funcionan las películas y las imágenes, ya que las películas son principalmente imágenes diferentes. Una fotografía está formada por millones de píxeles, cada píxel representa un punto en una imagen. Cada píxel es una representación de un punto de una imagen original, para poder representar cualquier color, cada píxel está formado por 3 componentes diferentes, que emiten luz de tres colores: rojo, verde y azul, con diferentes intensidades, para poder emitir cualquier color. Con todo esto, podemos decir que una sola foto se puede representar mediante tres matrices (una para cada color) que incluye la información de la intensidad que cada color debe tener en cada píxel. Sabiendo esto, podemos representar cada matriz como una superficie en un espacio tridimensional. Para obtener el límite de la arteria se calcularán las curvas de nivel, lo que nos permitirá determinar el área de la arteria.



*Ilustración 2: Curva de nivel representando la frontera de la arteria*

Después de procesar y filtrar los datos, se puede obtener una señal clara de la evolución del área de una arteria a lo largo del tiempo.



*Ilustración 3: Salida final de la evolución del área lo largo del tiempo*

### 3. Conclusiones

El método propuesto determina los cambios en el área de la arteria y es capaz de proporcionar una salida continua de datos que tiene la misma forma de onda que el flujo cardíaco. También puede detectar pequeños cambios generados por la respiración en el

área de la arteria. Las mediciones obtenidas a partir del análisis de vídeos de ultrasonido parecen proporcionar información válida en la mayoría de las ocasiones. El método propuesto es especialmente preciso al determinar los cambios en la amplitud de la señal que representa el área de la arteria. La solución propuesta también fue capaz de determinar correctamente la evolución del área promedio en la mayoría de los vídeos analizados.

# **CALCULATION OF THE PERIPHERAL ARTERY'S AREA THROUGH ULTRASOUND IMAGING**

**Author: Izaguirre de Benito, Álvaro.**

**Director: Oldham, Kenn.**

**Collaborating Entity: University of Michigan.**

## **SUMMARY**

### **1. Introduction**

The work carried out has consisted in studying, in a non-invasive way, the evolution of the area of an artery.

The state and behaviour of the arteries are essential physiological indicators; knowing these indicators allows us to predict how the body can respond to acute and chronic diseases.

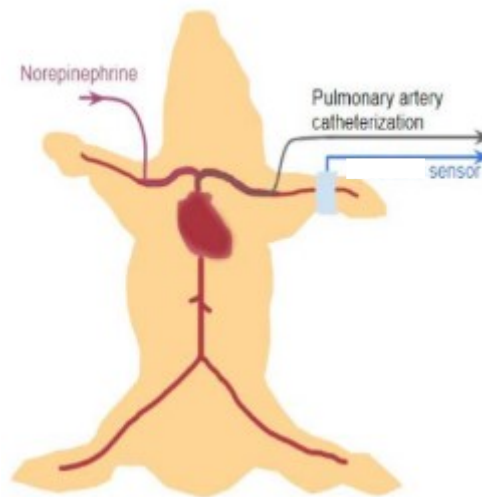
Vascular tone refers to the degree of constriction of the arteries relative to a state where the artery is completely dilated, it can be used as an indicator of how will the body respond to situations of cardiovascular stress (situations where there is no normal behaviour such as haemorrhages). Vascular tone is one of the most important factors when evaluating the systemic vascular resistance of the body, or the resistance felt by the heart when pumping blood through the vascular system to all the cells in our body. Vascular tone is one of the most important mechanism of compensation the body has to maintain physiological homeostasis (which refers to the body's tendency to maintain physiological parameters -such as blood pressure and body temperature- of its internal environment within specific ranges of values. [WANG17][PEAR12]

However, being able to determine vascular tone can be difficult to assess using the technologies available today, even more when vascular tone is being evaluated non-invasively. Most of the non-invasive technologies have problems of complexity (as they

require a certain type of expertise or the instruments needed are complex), precision or do not provide a continuous measurement. All these limitations will be faced in our proposed solution.

The sensor chosen to obtain the information about the state of the artery is an ultrasound device. Ultrasound imaging is based on the same principles involved in the sonar technology which is used by different animals such as bats to “see” what is around them. When a sound wave strikes an object part of the sound bounces back. By measuring these sound waves that bounce back, it is possible to determine how far away the object is as well as the object's size, shape and consistency (whether the object is solid or filled with fluid). [RADI18]

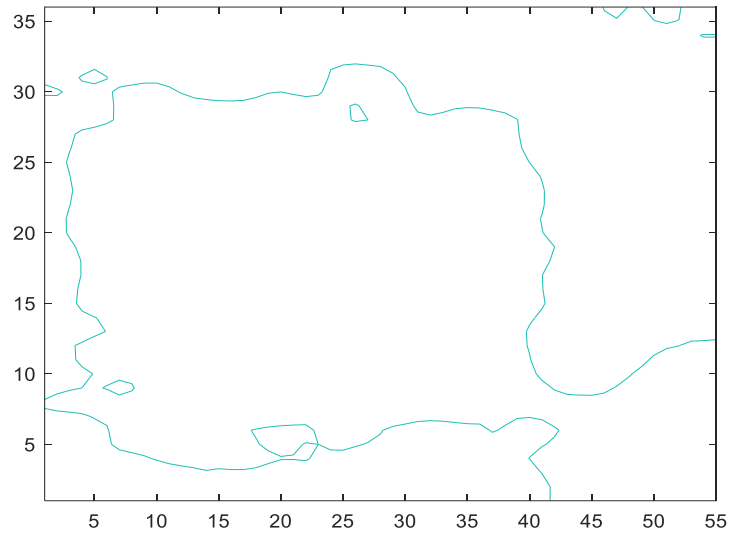
In order to get the information to develop the solution and check the results obtained it will be necessary to conduct an experiment on an animal. A swine will be used to extract all the information required for this experiment. The swine test subject was anesthetized for cardiovascular testing and manoeuvres were performed subject to University of Michigan animal protocol PRO00006553. Mean arterial pressure and cardiac output were tracked invasively using pulmonary artery catheterization. The ultrasound sensor was placed on one of the swine's limbs, providing a cross section of the radial artery. To induce changes in systemic vascular resistance, periodic infusions of norepinephrine were used. Norepinephrine triggers vasoconstriction (narrowing of blood vessels) specifically that of small blood vessels, which increases blood pressure. [WANG18]



*Illustration 4: Swine and sensor disposition during the experiment  
[WANG18]*

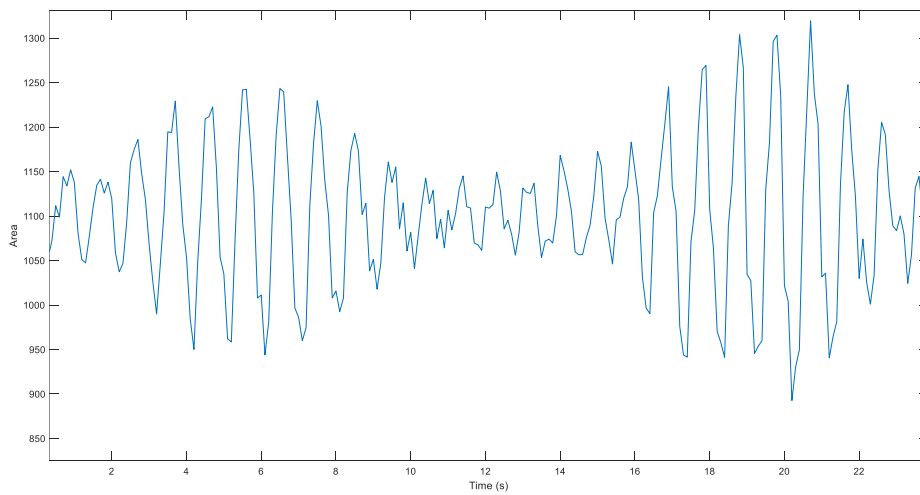
## **2. Approach**

The vascular tone can be measured by calculating the area of arteries. To do so, videos of the evolution of the artery were obtained from the ultrasound sensor. The method used to calculate the area is based on how movies and pictures work, as movies are mainly a sequence of different pictures. A photograph is formed by millions of pixels, each pixel represents a point in a picture. Each pixel is a representation of a point in an image, to be able to represent any colour each pixel is formed by 3 different components, which emit light of three colours: red, green and blue, at different intensities, to be able to emit any colour. Based on this, we can say that a single photo can be represented by three matrices (one for each colour) that include the information of the intensity that each colour must have at every pixel. Knowing this, we are able to represent each matrix as a surface on a three-dimensional space. To obtain the boundary of the artery, level curves will be calculated, which will allow us to determine the area of the artery.



*Illustration 5: Contour representing the boundary of the artery*

After the data is processed and filtered a clear signal can be obtained of the evolution of the area of the artery along time.



*Illustration 6: Final data output of the evolution of the area of the artery in time*

### **3. Conclusions**

The method proposed to determine changes in the area of the artery is capable of providing a continuous output of data that has the same wave form as the cardiac output.

It can also detect small changes generated by breathing in the area of the artery. The measurements provided from the analysis of the ultrasound video seem to provide valid information in most of the occasions. The method proposed is especially precise when determining the changes in the amplitude of the signal that represents the area of the artery. The solution proposed was also capable of correctly determining the evolution of the average area in most of the videos analysed.



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# 1. Introduction

The state and behaviour of the arteries are essential physiological indicators; knowing these indicators allows us to predict how the body can respond to acute and chronic diseases.

Vascular tone refers to the degree of constriction of the arteries relative to a state where the artery is completely dilated, it can be used as an indicator of how will the body respond to situations of cardiovascular stress (situations where there is no normal behaviour such as haemorrhages). Vascular tone is one of the most important factors when evaluating the systemic vascular resistance of the body, or the resistance felt by the heart when pumping blood through the vascular system to all the cells in our body. Vascular tone is one of the most important mechanism of compensation the body has to maintain physiological homeostasis (which refers to the body's tendency to maintain physiological parameters -such as blood pressure and body temperature- of its internal environment within specific ranges of values.[WANG17][PEAR12]

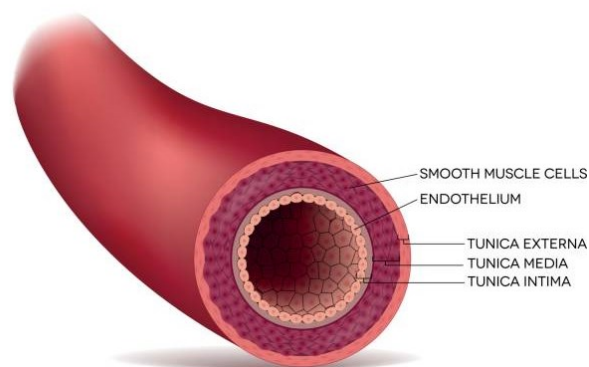
There are many factors which determine the vascular tone, but they can be differentiated into two groups regarding their effect on the radius of the blood vessel: vasoconstrictors (which make blood vessels narrower) and vasodilators (which make blood vessels wider). These factors can also be separated from their source into extrinsic factors, which come from places other than the tissue or organ where the blood vessel is located, and intrinsic factors, in which the source is the blood vessel itself or the surrounding tissue. The main function done by extrinsic factors is to regulate arterial blood pressure by altering systemic vascular resistance, whereas intrinsic mechanisms are the ones responsible for the local blood flow regulation within an organ. Vascular tone at any given time is determined by the balance of competing vasoconstrictor and vasodilator influences. [KLAB18]

The two most relevant factors that influence vascular tone will be explained:

**a) Endothelium (intrinsic)**

The endothelium may seem small, as it is a one cell layer (1-2 microns thick) sitting on top of a layer of smooth muscle cells (the media) and a thick layer of connective tissue (the adventitia). If taken as a whole, the endothelium represents a large surface where information is exchanged between the blood and the vascular smooth muscle tissue. In a 70 kg adult the endothelium covers an area of 700 m<sup>2</sup> and weighs 1000-1500 grams, which is comparable to the liver's mass. A healthy endothelium allows for mechanical to chemical signal transduction to maintain homeostasis of the blood vessel. [ALLE14]

One of the principal functions of the vascular endothelial cells is the regulation of blood vessel tone, inflammatory processes, antithrombosis, and anticoagulation. Endothelial cells generate vasoconstriction of the blood vessels through endothelin. Endothelium achieves vasodilation using nitric oxide (NO), prostacyclin, and endothelial derived hyperpolarizing factor. [ALLE14]



*Illustration 7: Cross section of an artery [iStock]*

### **b) Neuronal and Hormonal mechanisms (extrinsic)**

The heart and vascular system are also regulated by the nervous system, precisely by the autonomous nervous system (which we do not have control over and is in charge of vital functions such as the respiration or cardiac frequency). These neural mechanisms mainly involve sympathetic adrenergic (nerves that travel along arteries) and parasympathetic cholinergic (which stimulate production of hormones), both branches of the autonomic nervous system. The sympathetic system stimulates the heart to increase its frequency and causes contraction of the vascular smooth muscle that results in the vasoconstriction of the blood vessels. The parasympathetic system reduces cardiac function and dilates selected blood vessels. [KLAB18]

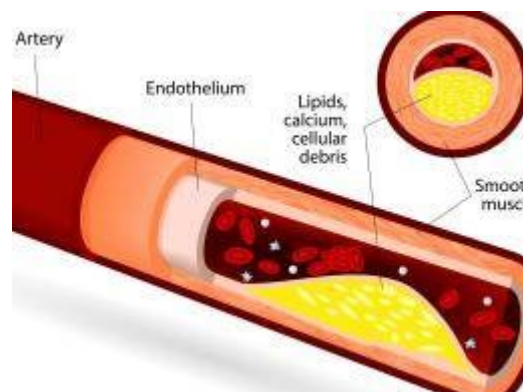
The hormonal system has multiple mechanisms to regulate the state of the cardiovascular system, some of them are: circulating catecholamines, the renin-angiotensin-aldosterone system, vasopressin (antidiuretic hormone), atrial natriuretic peptide, and endothelin. Each of these hormonal systems can directly or indirectly alter cardiac function, vascular function, and arterial pressure. [KLAB18]

## 1.1 Diseases

Vascular tone can be affected by multiple diseases and being able to detect those changes can be crucial when treating or diagnosing patients. Some of these diseases are:

### a) Atherosclerosis

Arteriosclerosis occurs when arteries become thick and stiff, to the point where blood flow to cells can even be depleted. Atherosclerosis is a certain type of arteriosclerosis. Atherosclerosis refers to the phenomenon in which different kind of substances (fats, cholesterol...) build-up the artery walls forming what is known as plaque, which can restrict blood flow.



*Illustration 8: Atherosclerosis [Medical News Today]*

The plaque can burst, triggering a blood clot which can block blood flow to organs. If this clot ends in one of the coronary arteries it would cause a myocardial infarction resulting in the death of cardiac muscle. If the clot would block blood flow to the brain it would be a cerebral stroke, which can cause brain damage. These cells cannot be regenerated by our body, which make its consequences long lasting. [AMER17] [MAYO18]

Knowing what the possible effects of atherosclerosis are, it is vital to make an early diagnostic. It has been proven that acetylcholine, a neurotransmitter that causes vasodilation in order to activate muscles, has the opposite effect on patients with atherosclerosis, as it causes vasoconstriction and even temporary occlusion, reducing

blood flow to different parts of the body. Being able to determine the evolution of vascular tone of patients that are injected with acetylcholine, could help doctors diagnose patients with atherosclerosis. [LUDM86]

## **b) Sepsis**

Sepsis is one of the most fatal diseases in the world, it brings more people to the hospital than people with heart attack or stroke combined, it is responsible of 33-50 % of all in-hospital deaths. [PRES16]

Sepsis is a condition caused by the body's response to an infection. The body normally releases chemicals into the bloodstream to fight an infection. Sepsis occurs when the body's response to these chemicals is out of balance, triggering changes that can damage multiple organ systems. If sepsis progresses to septic shock, blood pressure drops dramatically and could lead to death. When this pressure drops dramatically, vascular tone increases by reducing the radius of arteries to achieve physiological homeostasis. [MAYO18]

## 1.2 Current procedures

There are several ways that vascular tone can be assessed in a non-invasive way. They will be presented:

- a) **Ultrasound and Flow Mediated Dilation.** This method uses Doppler ultrasound technology to study vascular tone, this apparatus provides information about internal tissue and blood speed. The data obtained is not continuous but an average through time, and the procedure must be repeated every time to obtain new results. The procedure is complex with multiple steps. Technicians are required to complete at least 100 scans annually to maintain expertise. This procedure allows to calculate vascular tone but also mean flow (ml/min) and shear stress on the vessel wall. [ALLE14]
  
- b) **Arterial Tonometry and Cuff reference.** In this process two finger cuffs (with incorporated plethysmographic probes) are used, each one is placed on a different hand covering the distal two thirds of the fingers, and another cuff is placed in one upper arm. The upper arm cuff is inflated for five minutes to suprasystolic pressures, this interrupts blood flow to the fingers which increases Nitric Oxide production to open the vessels. After five minutes the upper arm pressure cuff is released, restoring blood flow, and data from the plethysmograph is compared with the data obtained when there was no blood flow. [KAND13]
  
- c) **PPG (Photoplethysmography) amplitude + Flow mediated dilation.** PPG is a sensor (usually placed on the finger tip) that measures dynamic blood volume changes, it does it by measuring the light absorbed by blood. In this process, blood flow is interrupted using an inflating cuff, after 4 minutes blood flow is restored and PPG data is studied to evaluate endothelial function. [ZAHE10]



Table 1: Comparison of previous non-invasive technologies

Prior Techniques	Advantages	Limitations
Ultrasound + Flow Mediated Dilation	Closest to a gold standard, agrees with measures of closely related variables.	Requires specialized equipment and expertise, non-continuous measurement.
Arterial Tonometry + Cuff reference	Absolute volume changes available using pressure reference.	Specialized hardware, non-continuous measurement; testing requires pumps for pressure reference and cuff occlusion.
PPG (Photoplethysmography) amplitude + Flow mediated dilation	Simplified sensing elements	Testing requires pumps for pressure reference and cuff occlusion.

As it can be seen, most of these technologies have problems of complexity (as they require a certain type of expertise or the instruments needed are complex), precision or do not provide a continuous measurement. All these limitations will be faced in our proposed solution.

## 1.3 Objectives

The goal of this project is to monitor changes in the area of a peripheral artery, to be able to determine vascular tone and related cardiovascular properties. These measurements will provide essential information about the state of the cardiovascular system to doctors so they would be able to diagnose medical conditions, treat them and study the evolution of the cardiovascular system.

The method should check the following objectives:

### a) **Non-invasive technology**

Introducing sensors in the body is never easy and requires expertise to avoid problems when introducing them. Potential risks from using invasive sensors in the vascular system include bleeding, infection and sometimes even death. Also invasive sensors can introduce changes in the cardiovascular system as the body may react to them in unpredictable ways. as doing invasive measurements on the vascular system can be risky to the patient as haemorrhage can occur while using these systems.

### b) **Continuous data output**

Being able to study how the cardiovascular system is behaving at all times can give doctors information about any condition the patient may have and how to properly treat them. Knowing the state of the vascular system of the patient at all times can be helpful while diagnosing.

### c) **Precision**

Arteries are not very big, especially the ones that are closer to the skin (for example, the radial artery -which is relatively close to the skin- has a diameter of 2 millimetres). Thus, changes on peripheral arteries can be very small, this is why precision will be required to detect those small changes.

**d) Using a non-expensive existing technology**

The sensor used to study the evolution of the arteries' area must be already available and the proposed solution must be easy to replicate. This is done to be able to extend this technology to everyone.

**e) Little training needed**

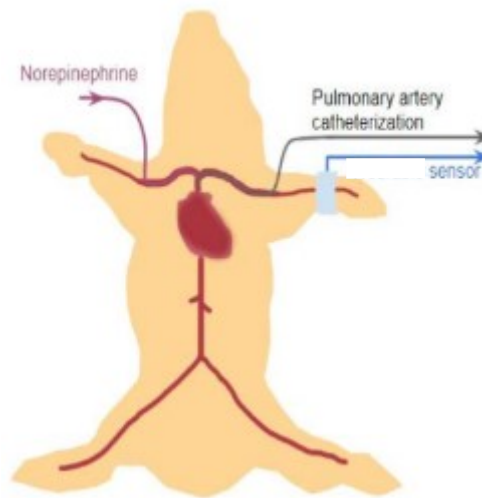
The main purpose is that doctors do not need long training to be able to evaluate how the artery area changes. The tool should be user friendly to make it accessible to doctors.

## 1.4 Resources

The sensor chosen to obtain the information about the state of the artery is an ultrasound device. Ultrasound imaging is based on the same principles involved in the sonar technology which is used by different animals such as bats to “see” what is around them. When a sound wave strikes an object, part of the sound bounces back. By measuring these sound waves that bounce back, it is possible to determine how far away the object is as well as the object's size, shape and consistency (whether the object is solid or filled with fluid).

During a medical ultrasound examination, a transducer (sensor) both sends the sound waves into the body and receives the sound waves which bounce back on the cells. When the transducer is pressed against the skin, it directs small pulses of high-frequency (1-18 MHz) sound waves into the body which cannot be heard by our ears. As the sound waves bounce off internal organs, fluids and tissues, the sensitive receiver in the transducer records tiny changes in the sound's pitch and direction. These signature waves are instantly measured and displayed by a computer, which in turn creates a real-time picture on the monitor. This will allow to evaluate changes in the artery in a non-invasive and not harmful way. [RADI18]

In order to get information to develop the solution and check the results obtained it will be necessary to conduct an experiment on an animal. A swine will be used to extract all the information required for this experiment. The decision of using a swine in the experiment was made because, although a swine and a human may look very different, their cardiovascular systems are very similar, to the point that when humans need new heart valves, sometimes swine's heart valves are transplanted to human patients.



*Illustration 9: Swine and sensor disposition during the experiment [WANG18]*

The swine test subject was anesthetized for cardiovascular testing and manoeuvres were performed subject to University of Michigan animal protocol PRO00006553. Mean arterial pressure and cardiac output were tracked invasively using pulmonary artery catheterization. The ultrasound sensor was placed on one of the swine's limbs, providing a cross section of the radial artery. The radial artery was the one being studied as it is a relatively big artery (around 2 mm in diameter), and it is close to the surface, this would allow us to get a clear view in the ultrasound as there would not be much tissue between the transponder and the artery. The videos information from the ultrasound sensor were used in our study and was the only input received. The invasive information was used to check the measurements obtained from the method proposed. [WANG18]

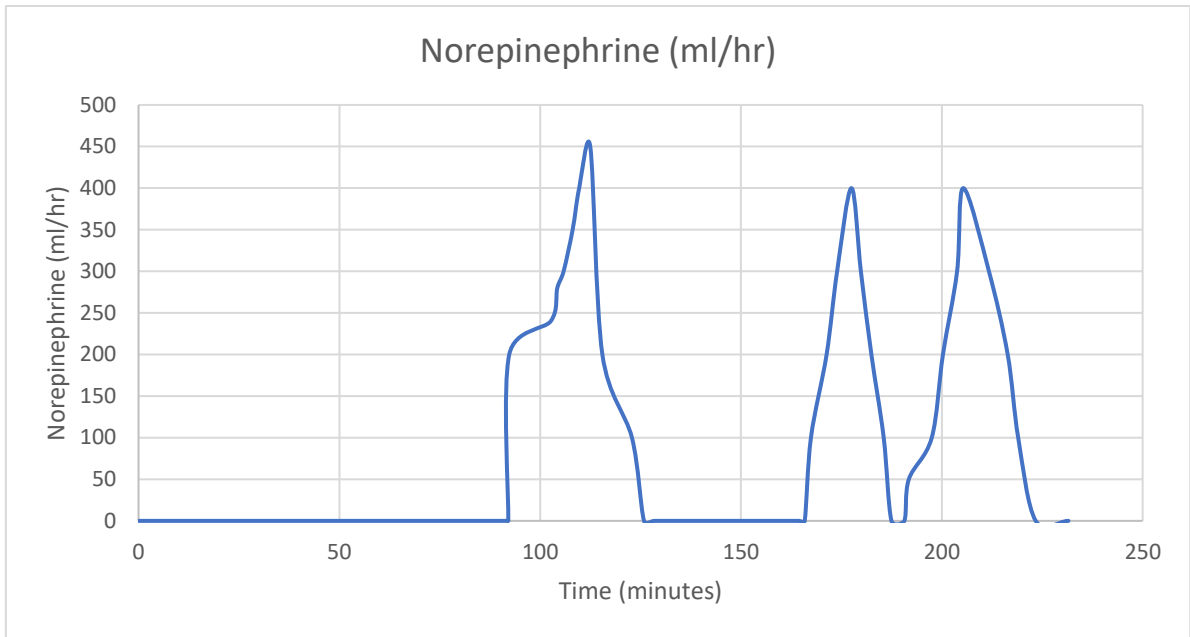
To induce changes in systemic vascular resistance, periodic infusions of norepinephrine were used. Norepinephrine, also called noradrenaline, is a substance that is released predominantly from the ends of sympathetic nerve fibres and that acts to increase the force of skeletal muscle contraction and the rate and force of contraction of the heart. The actions of norepinephrine are vital in situations where fight-or-flight response is required, whereby the body prepares to react to or retreat from an acute threat. In the blood vessels, it triggers vasoconstriction (narrowing of blood vessels) in particular

that of small blood vessels, which increases blood pressure. Blood pressure is further raised by norepinephrine as a result of its effects on the heart muscle, which increases the blood output from the heart. [ROGE15] [MART15]

The experiment was four hours long. In total three norepinephrine infusions were injected to the swine from a cardiovascular steady state. The infusion flow was manually controlled by a valve with a constant norepinephrine concentration. The norepinephrine infusions did not start until instruments were checked and the swine reached a situation of cardiovascular normality, after invasive sensors were inserted. When the state of cardiovascular normality was achieved, measurements were taken to study the normal cardiovascular situation of the swine. After these measurements were taken, norepinephrine infusions started with increasing flow (ml/hr) peaking at around 400-450 ml/hr, then the flow was progressively reduced to zero. Between the first and the second norepinephrine infusions time was allowed to pass to let cardiovascular situation return to normal. The time between the second and third infusions was shorter than between the first and the second.

Table 2: Norepinephrine flow during the experiment

Time	Norepinephrine (ml/hr)
11:50:19	0
12:31:31	0
12:32:27	0
13:22:23	0
13:22:37	200
13:32:57	240
13:34:35	280
13:36:09	300
13:38:24	350
13:40:02	400
13:42:47	450
13:45:48	200
13:53:10	100
13:56:10	0
14:34:51	0
14:36:11	0
14:37:44	100
14:41:38	200
14:44:15	300
14:47:49	400
14:50:10	300
14:52:47	200
14:55:51	100
14:57:47	0
15:00:59	0
15:02:06	50
15:07:49	100
15:10:36	200
15:14:07	300
15:15:40	400
15:22:03	300
15:26:43	200
15:29:20	100
15:33:42	0
15:41:51	0



*Illustration 10: Norepinephrine flow during the experiment*

The program used to analyse the videos was MATLAB, which provides powerful tools when programming. MATLAB is also very useful when working with video files due to its immense flexibility and the amount of resources.





## **2. Procedure**

As mentioned earlier, the information that was studied were different ultrasound videos of transversal section of a peripheral artery, the radial artery. The objective is to obtain a clear signal from the data.

This section will be divided into two parts: data acquisition and signal treatment.

### **2.1 Data acquisition**

The method used to calculate the area is based on how movies and pictures work, as movies are mainly a sequence of different pictures. A photograph is formed by millions of pixels, each pixel represents a point in a picture. Each pixel is a representation of a point in an image, to be able to represent any colour each pixel is formed by 3 different components, which emit light of three colours: red, green and blue, at different intensities, to be able to emit any colour. Based on this, we can say that a single photo can be represented by three matrices (one for each colour) that include the information of the intensity that each colour must have at every pixel. Knowing this, we are able to represent each matrix as a surface on a three-dimensional space. By analysing changes in colour intensity, changes in the artery's area will be determined.

The data was obtained from videos extracted during the experiments. The information displayed on these videos had this format:

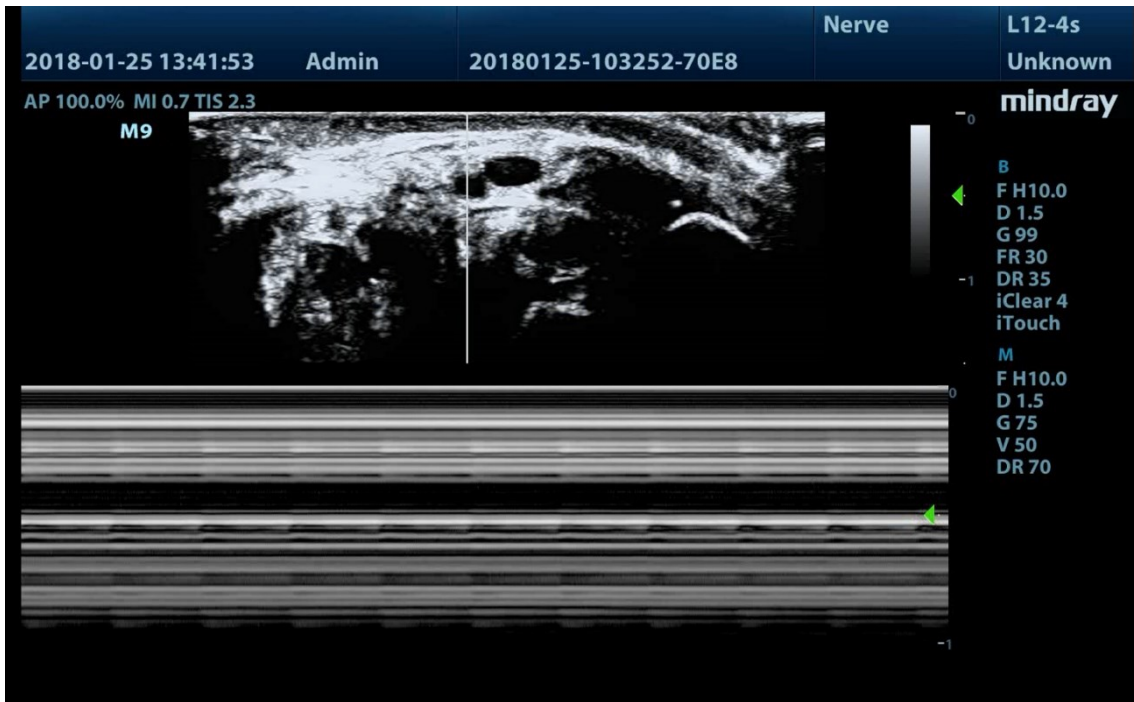


Illustration 11: Video format

But not everything that is displayed on these videos was subject to study, we focused on the following area as it is where the radial artery is:

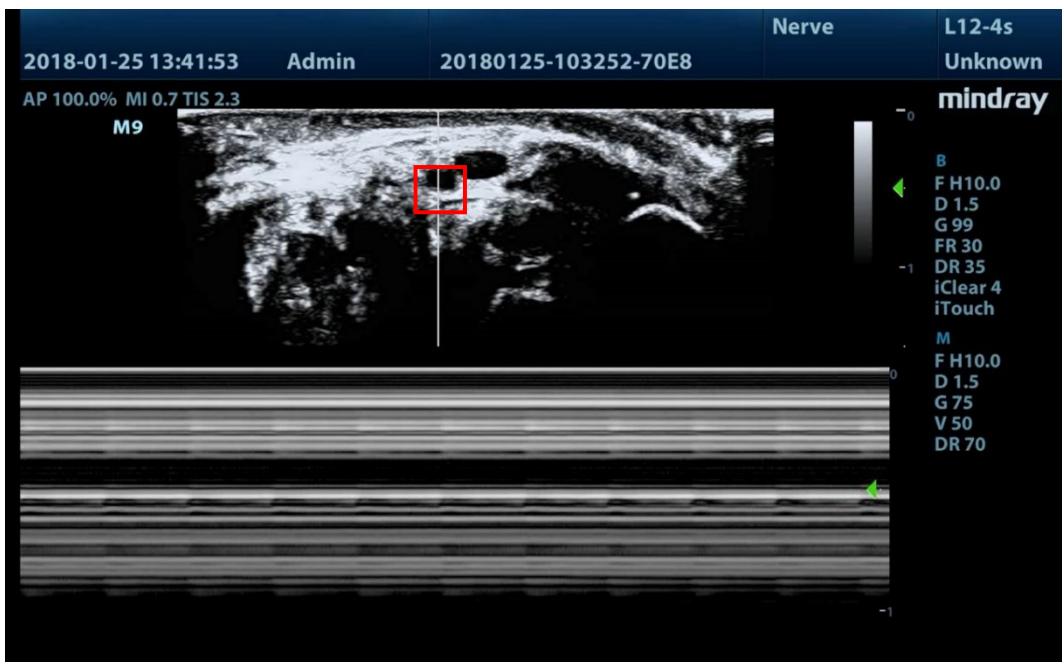
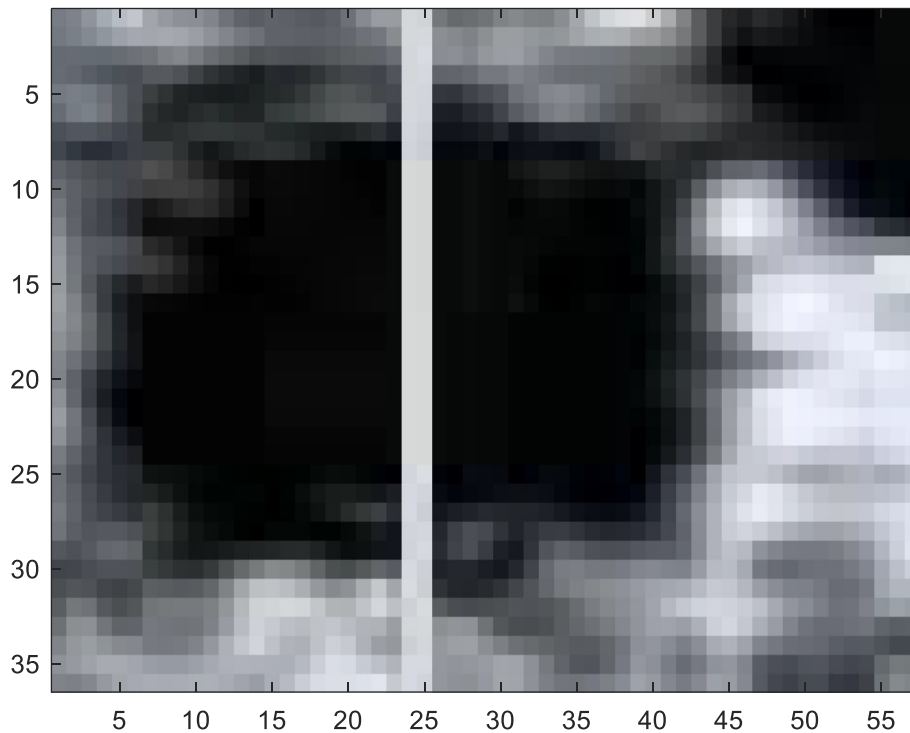


Illustration 12: Video with artery highlighted

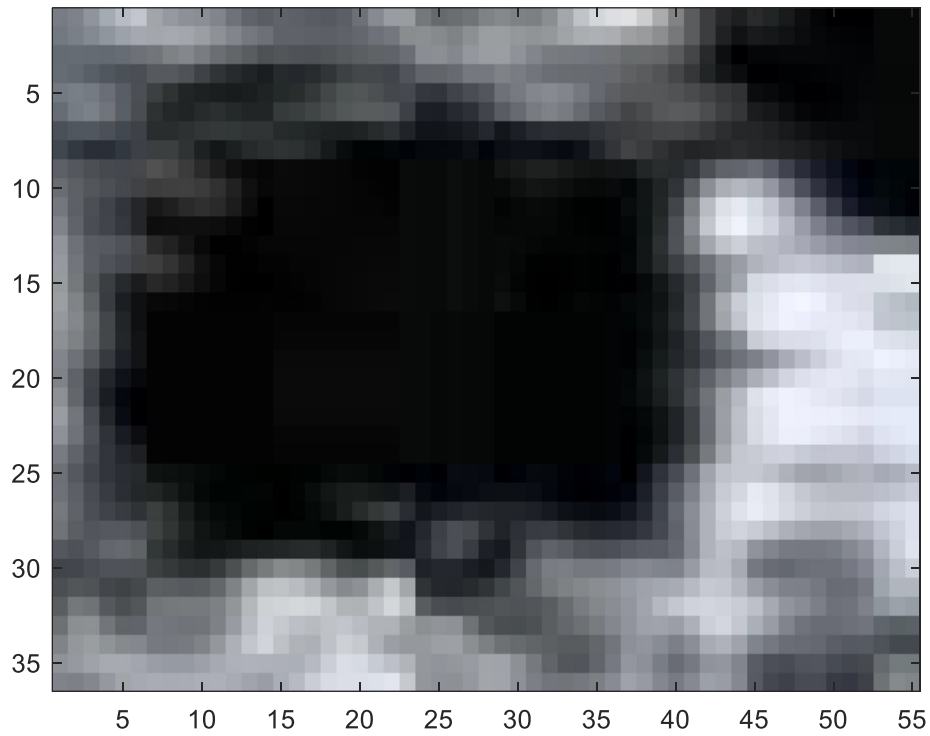
As we can see, the area subject to study is close to one vein not useful for our study. This vein, being so close to the artery, made it difficult to isolate the artery for our study.



*Illustration 13: Image of the artery*

As we can see in the picture above the area subject to study is very small, the definition is not very high and there is a white line that goes across the artery from the ultrasound video format.

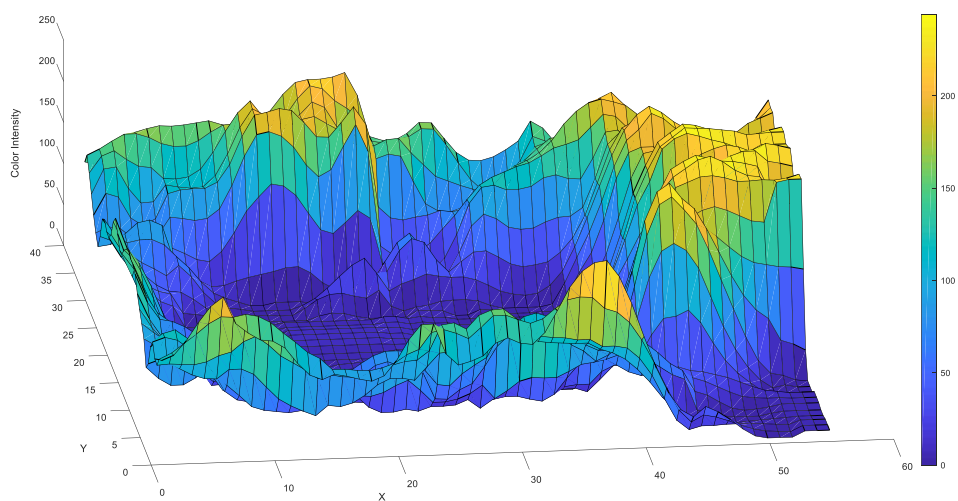
The first thing to be done was to remove the white line that goes across the artery that we were planning to study as it would hinder the study of how the artery behaves along time.



*Illustration 14: Image of the artery without the white line*

With the final clean picture, we can see that the boundary of the artery cannot be clearly differentiated from the tissue around it. The solution should maximize the signal quality so that valuable information could be extracted from it.

As mentioned earlier the data from each colour can be represented as a surface.



*Illustration 15: 3 D Representation of pixel intensity*

As we can see the in the 3D graph, there is a clear difference in the values of the red colour intensity which in the area of the artery are much lower than in the surrounding tissue (darker blues represent lower values and orange higher values). Knowing this we can obtain contour graphs or level curves to obtain this boundary:

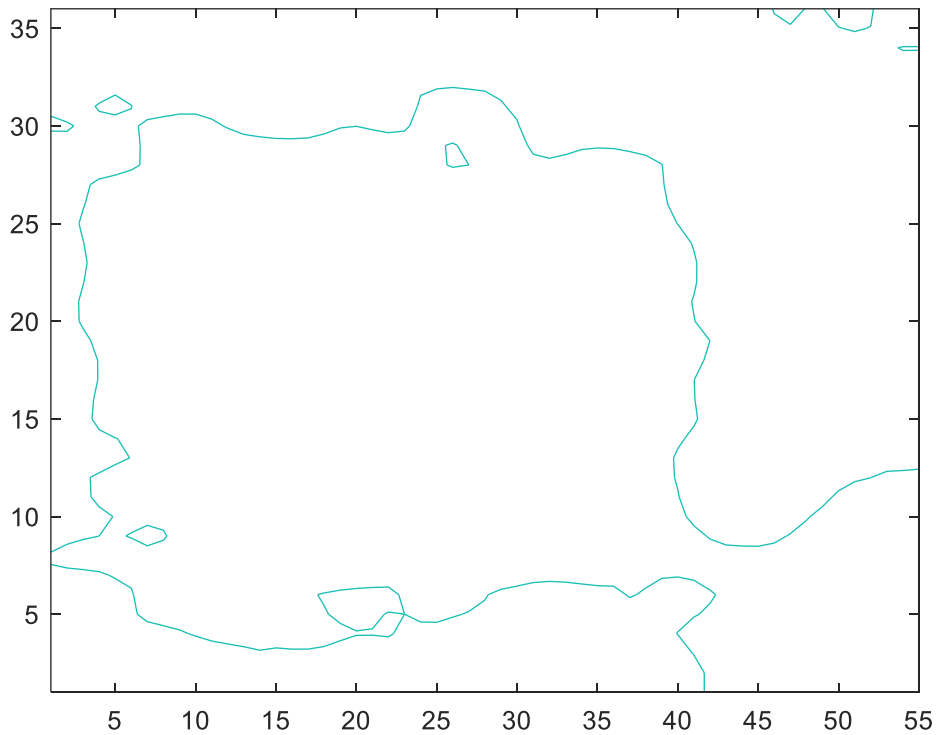


Illustration 16: Contour representing the boundary of the artery

As we can see the vein is interfering with the boundary of the artery as it forms a “bridge” between them. To solve this the artery was divided into two different halves and the one on the left was the one used in our study, then the results were multiplied by two to get the whole area. To do so the first frame of the video was used and the level curve with intensity value 40 was calculated, as it gets a completely closed plot. After doing this the centre of the artery in the x axis was calculated as:

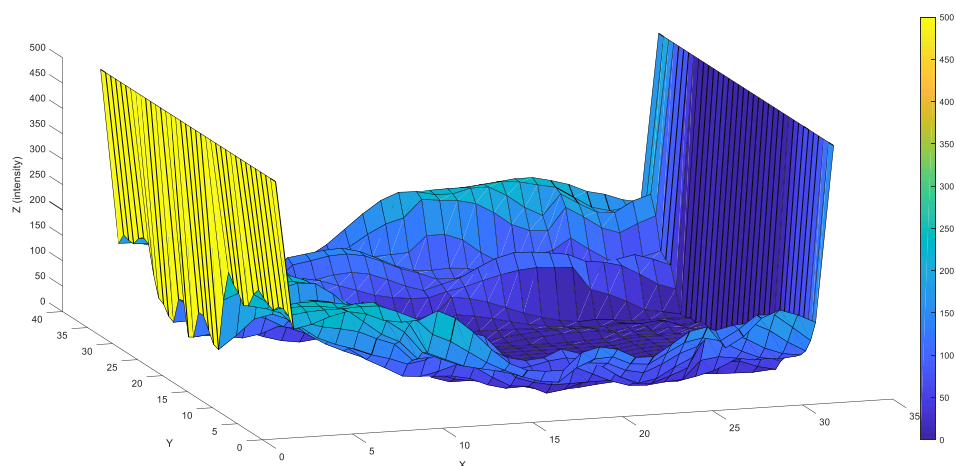
$$x_0 = \frac{\sum_1^n x_i}{n}$$

$x_i$ : x coordinate of the point  $i$  in the curve

Knowing the coordinate of this point we can now start calculating how the area of the artery changes along time.

For each frame we will now do:

- a) Get the pixel intensity information of the space where the artery is located.
- b) Erase the white line that goes across the artery, as mentioned earlier this does only hinder our analysis.
- c) Eliminate from the matrix the data that is on the right of the centre of the artery. This will be done using the coordinate calculated at the beginning of the analysis.
- d) In order to get a closed curve when calculating the contours, as some of them may not close, the data from the matrix will be enclosed in a bigger one with dimension  $(n+2,n+2)$  surrounded with values higher than anyone in the picture so this does not interfere with the real data.



*Illustration 17: 3 D Representation of pixel intensity with generated outer walls*

- e) Multiple contours will be calculated as it is difficult to determine what the exact boundary of the artery is from the video. These contours will be calculated as the

intersection between the surface generated with the colour intensity data and planes perpendicular to Z axis with the same distance between them. The distance chosen between the planes is 10 (intensity of colour). When analysing the final results this will be useful to determine which contour represents the real boundary of the artery.

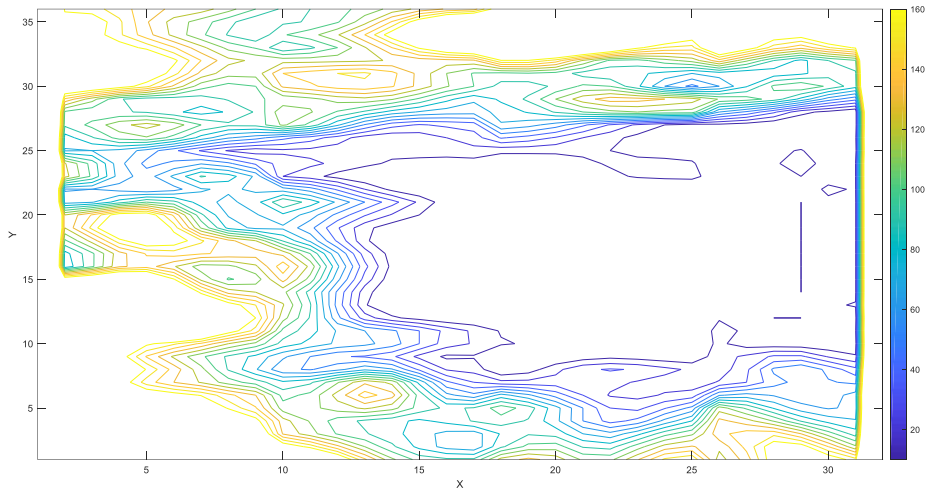


Illustration 18: Contours calculated

- f) Knowing the coordinates of the points in the contour, the area can be now calculated. The area will be calculated using the formula:

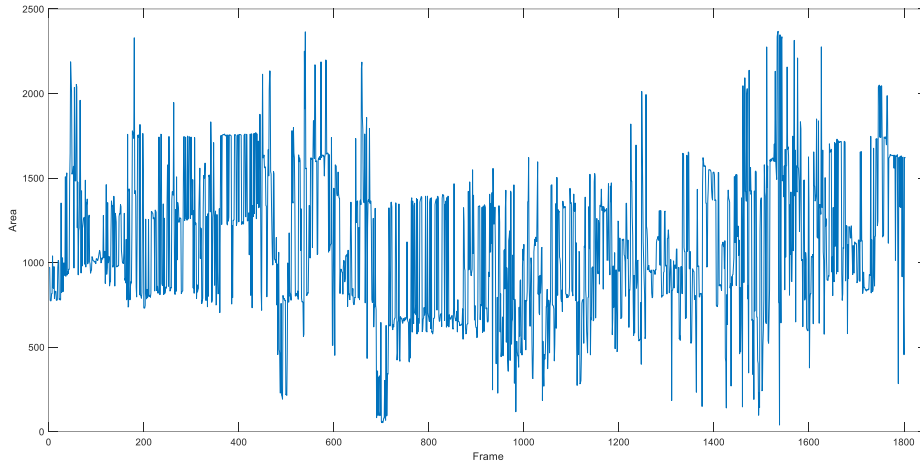
$$A = \left| \frac{(x_1y_2 - x_2y_1) + (x_2y_3 - x_3y_2) + \dots + (x_ny_1 - x_1y_n)}{2} \right|$$

$x_i$ : x coordinate of the point i in the curve

$y_i$ : y coordinate of the point i in the curve

Then this area will be multiplied by two to calculate the area of the whole artery, the values obtained will be saved in a matrix. The data obtained will look like this:





*Illustration 19: "Raw" data output*

As it can be seen, the data output is very noisy and there are no discernible patterns. This “raw” data will need some filtering so that information can be extracted from it.

## **2.2 Signal analysis**

As shown in the previous graph, the data output is very noisy, to extract some data from it the data will need to be filtered.

We will first start with a Fourier analysis to determine which frequencies are more relevant in our data.

### **Fourier analysis**

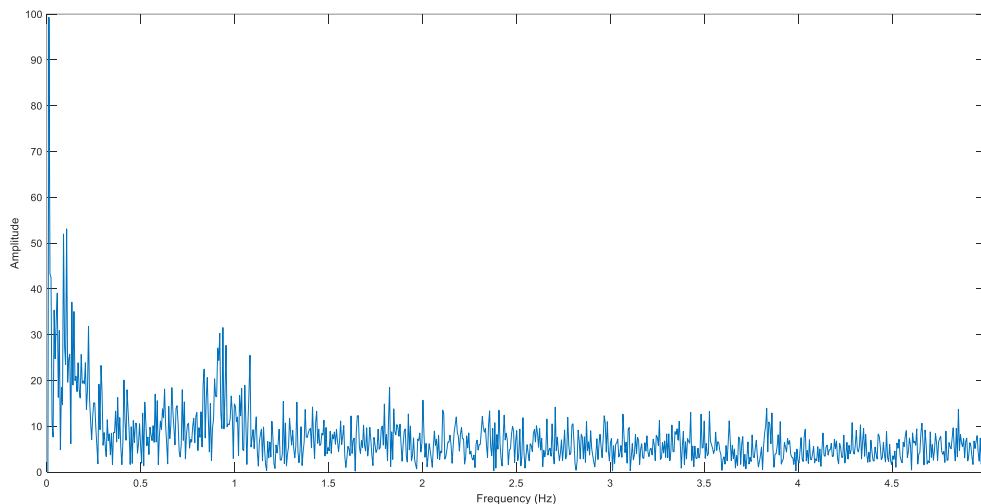
According to Fourier any function that is time dependant can be decomposed into the sum of multiple synodal function, and when added they result on the original function. Each of this synodal functions has its own amplitude, angular velocity and phase.

$$F(\omega) = \int_{-\infty}^{\infty} f(x) * e^{-i\omega t} * dt$$

The output is a function of angular velocity. This function returns complex number. The numbers can be expressed in a polar form:

$$a + b * i = \sqrt{a^2 + b^2} * e^{atan(\frac{b}{a}) * i}$$

When expressed on a polar form, we can see the amplitude of the sine at that frequency and the phase of the sine function. In this case the amplitude of each frequency will be studied.



*Illustration 20: Fourier Analysis*

We can see in the representation of the amplitudes above that there are frequencies that are more relevant than others. We can see that around 0.9 Hz there is a peak that would correspond to the swine's heartbeat frequency as swines present a normal heart rate of 60 beats per minute.

Once we have the most dominant frequencies, noise will be removed so information can be extracted. Three different filters will be used in this signal analysis phase: a look forward look back filter, a low pass filter and band pass filters. These filters will be explained in the order they were applied.

### **Look forward look back filter**

The purpose of using this filter is to reduce the abrupt changes in the data obtained taking into account that the information is periodic as shown in the Fourier analysis. To do so, the value of the area at each point in time will be calculated as the average of the value of the area calculated at each point and two intervals before it and two intervals after it.

With the dominant frequency we have obtained, we will divide the frame rate of the video between the dominant frequency value, the frame rate in the videos used is 10 frames per second. This will give the intervals we will need to apply the look back look forward filter.

$$I = \frac{10}{F_0}$$

$$E(n) = \frac{R(n - 2 * I) + R(n - I) + R(n) + R(n + I) + R(n + 2 * I)}{5}$$

*I: frame intervals*  
*F<sub>0</sub>: dominant frequency*  
*E: calculated data*  
*R: "raw" data*

If the resulting interval value is not an integer, we will use a combination of two different intervals. For example, if the calculated interval is 10.36 frames, we will use intervals of 10 and 11 frames. The E formula will look like this:

$$E(n) = \frac{R(n - 2 * 10) + R(n - 2 * 11) + R(n - 10) + R(n - 11) + R(n) + R(n + 10) + R(n + 11) + R(n + 2 * 10) + R(n + 2 * 11)}{9}$$

Once this has been applied, we will use two additional filters. As mentioned earlier, a low pass filter will be the next one.

### **Low pass filter**

This filter will remove high frequency noise from our signal. As seen in our first Fourier analysis, high frequencies were not significant as their amplitude is relatively small compared to the dominant frequency and its harmonics. Although performing a low pass filter may seem trivial when band pass filters are also applied, this low pass filter will help us further damp high frequencies.

Frequencies higher than 10 Hz will be removed using the following filter:

$$\omega_0 = 2 * \pi * 10$$

$$G(s) = \frac{\omega_0^2}{s^2 + 2 * \omega_0 * s + \omega_0^2}$$

### **Band pass filter**

This filter will be used to keep the information of the dominant frequency and its first four harmonic frequencies, the others will be damped. The formulas used to design this filter are:

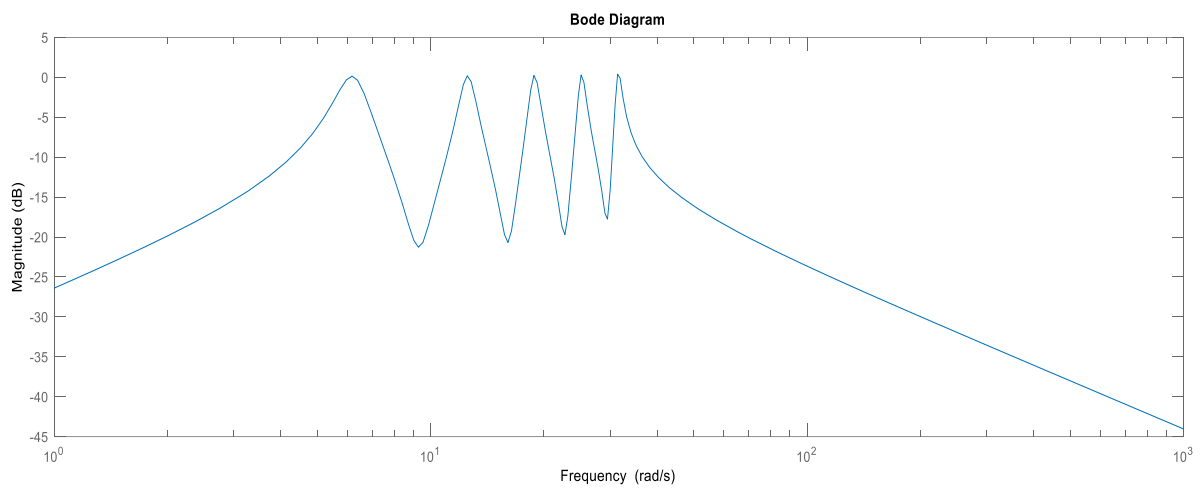
$$F_0 = \sqrt{F_H * F_L}$$

$$\omega_0 = F_0 * 2 * \pi$$

$$Q_0 = \frac{F_0}{F_H - F_L}$$

$$G(s) = \frac{\frac{\omega_0}{Q_0} * s}{s^2 + \frac{\omega_0}{Q_0} * s + \omega_0^2}$$

The resulting bode diagram from this five band pass filters is:

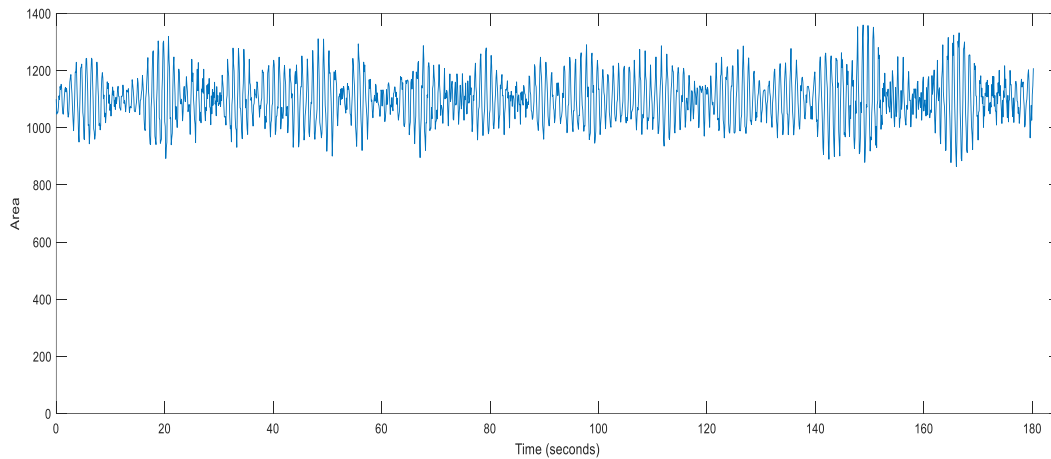


*Illustration 21: Bode diagram of the band pass filters*



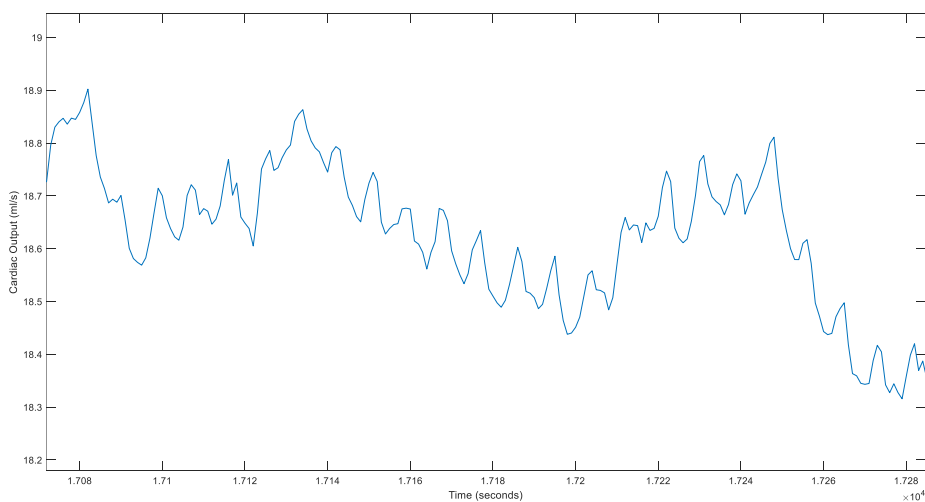
### 3. Results analysis

After all the filters have been applied the data can be finally analysed. The final plot of the evolution of the area is the following.

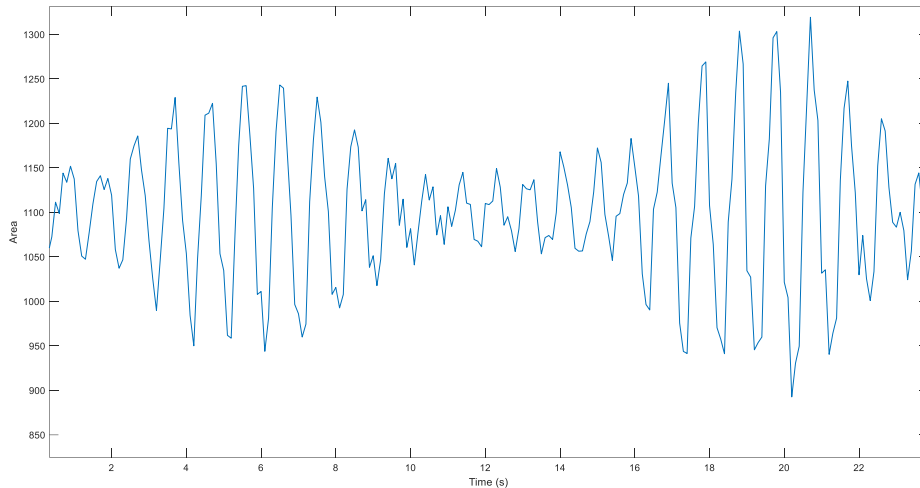


*Illustration 22: Final data output of the evolution of the area of the artery in time*

The first thing that can be seen from looking at the data is that changes in the area are not very big, they average 8%. These changes are generated by each heartbeat which increases pressure when pumping blood through the arteries.



*Illustration 23: Evolution of cardiac output in time*



*Illustration 24: Breathing induced amplitude changes*

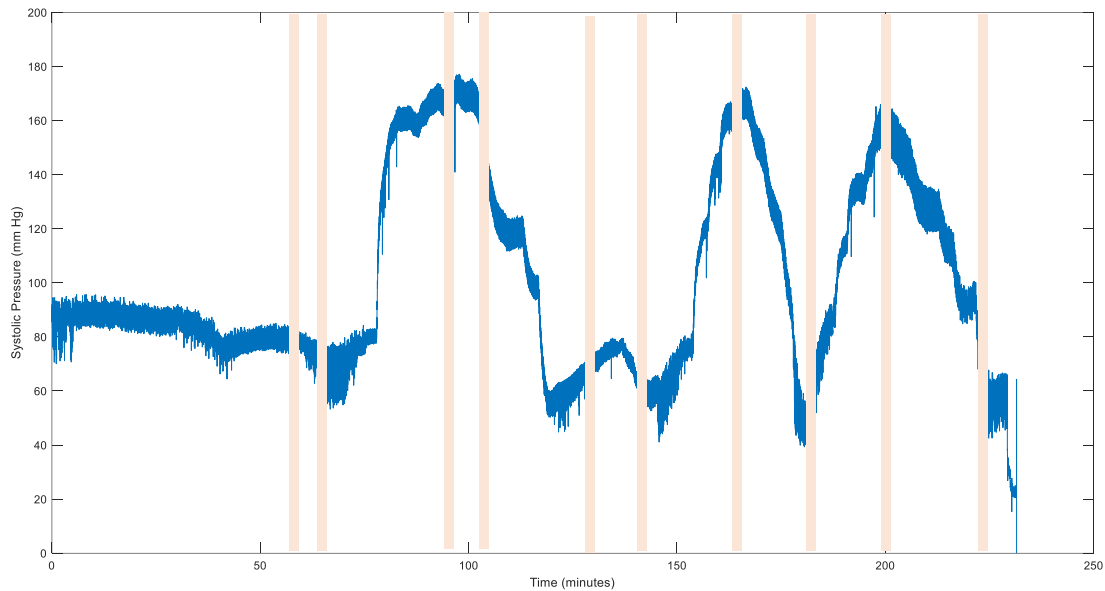
It can be observed that the data obtained is similar to the plotted cardiac output. This was expected as cardiac output can be calculated as the area of the cross section of an artery multiplied by the blood speed. It is important to say that it can be seen in both graphs that there is a smaller peak after each big peak, which would confirm the shape of the plot obtained.

As it can be seen the amplitude of the wave is not constant along time. The reason for this is that when we breathe our lungs get bigger, when they do this they exert pressure on the heart. The left side of the heart responds differently to the respiratory cycle. During inspiration, expansion of the lungs and pulmonary tissues causes pulmonary blood volume to increase, which transiently decreases the flow of blood from the lungs to the left atrium. Therefore, left ventricular filling actually decreases during inspiration. In contrast, during expiration, lung deflation causes flow to increase from the lungs to the left atrium, which increases left ventricular filling. The net effect of increased rate and depth of respiration, however, is an increase in left ventricular stroke volume and cardiac output. [KLAB18]

To validate the effectiveness of the method proposed, different videos were evaluated. By doing this the capability of being able to measure changes in the area will



be tested. Ten different videos were chosen, these videos were chosen using the information of the systolic pressure of the swine obtained during the experiment in moments when significant changes in the area were expected, as increases in systolic pressure will increase the area of the artery.



*Illustration 25: Systolic pressure during experiment and intervals studied*

The average area during the video was calculated and was compared with the Peripheral Vascular Resistance (PVR) that was calculated using the invasive information and the formula:

$$PVR = \frac{MAP - MVP}{CO}$$

*MAP: mean arterial pressure*  
*MVP: mean venous pressure*  
*CO: cardiac output (the blood flow)*

These measurements were also compared to the estimations of another non-invasive sensor that was being tested at the same time. The area of the artery should go down when the Peripheral Vascular Resistance goes up and the area should go up when the Peripheral Vascular Resistance goes down, this is because the PVR is inverse

to the area, as the vascular resistance of a blood vessel can be calculated from the area using the formula

$$R = \frac{8 * L * \mu}{\pi * r^4}$$

*R: resistance*  
*L: length of the blood vessel*  
*μ: viscosity of blood*  
*r: radius of the blood vessel*

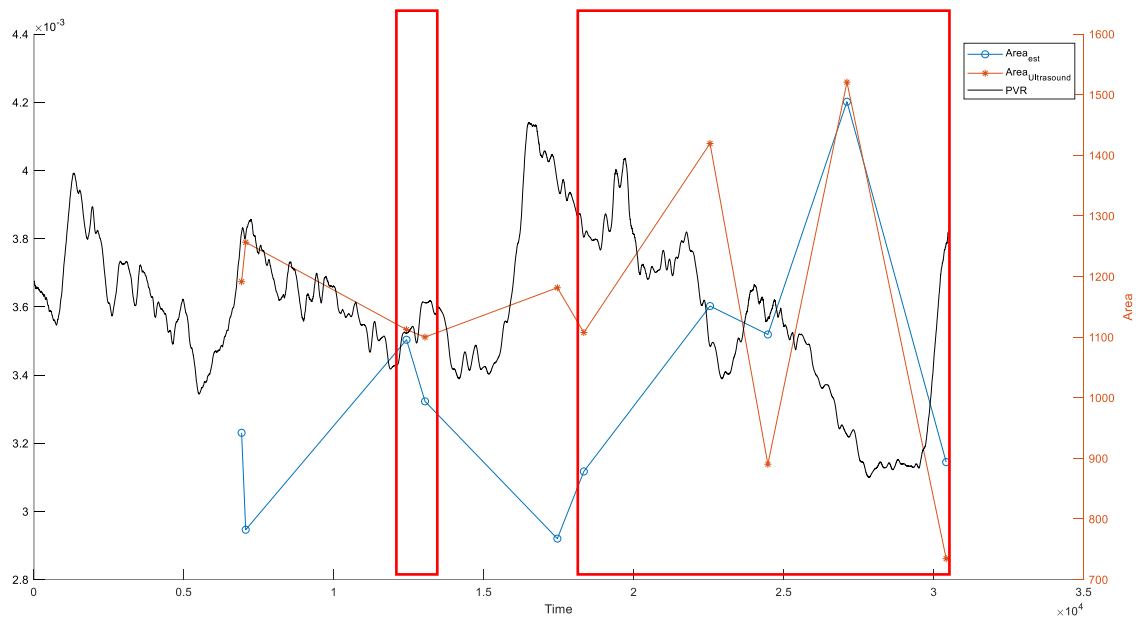
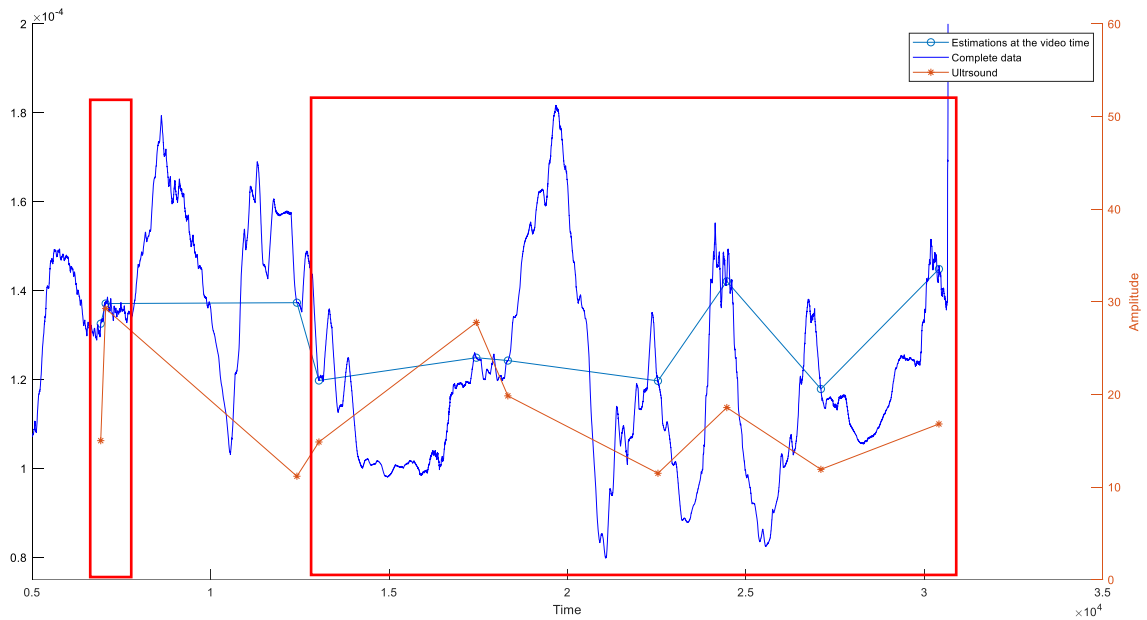


Illustration 26: PVR representation and area estimates. In the red square measurements that agree with invasive data

As it can be seen the data from the ultrasound is not always perfect and seems that changes towards the end would be in accordance with what was expected from the peripheral vascular resistance data.

The area oscillations will also be compared with the data obtained from the non-invasive sensor that was tested at the same time. To calculate these oscillations the

amplitude from dominant frequency (the one corresponding with the heartbeat  $\sim 1$  Hz) from the Fourier analysis is used.



*Illustration 27: Changes in the amplitude of the signal. In the red squares measurements that agree with estimated data*

As it can be seen, the measurements follow the same trend most of the cases. From the data obtained it can be said that the increase in pressure results in a smaller amplitude in the change of the artery's area. This phenomenon can be explained as when blood pressure increases arteries' smooth muscle cells contract, which can reduce the effect on the arteries' area produced by the heartbeats. It can be concluded that changes in the area generated by heart beats are not as significant when blood pressure has been increased. [KLAB18]



## 4. Conclusions

From the analysed data it can be concluded that ultrasound sensors are a valid solution to measure changes in the area of an artery. It can provide a continuous data output and is available at almost every medical facility in the world as it is not a very expensive sensor. It also does not require too much training for a doctor as they only need to find an artery using ultrasound equipment.

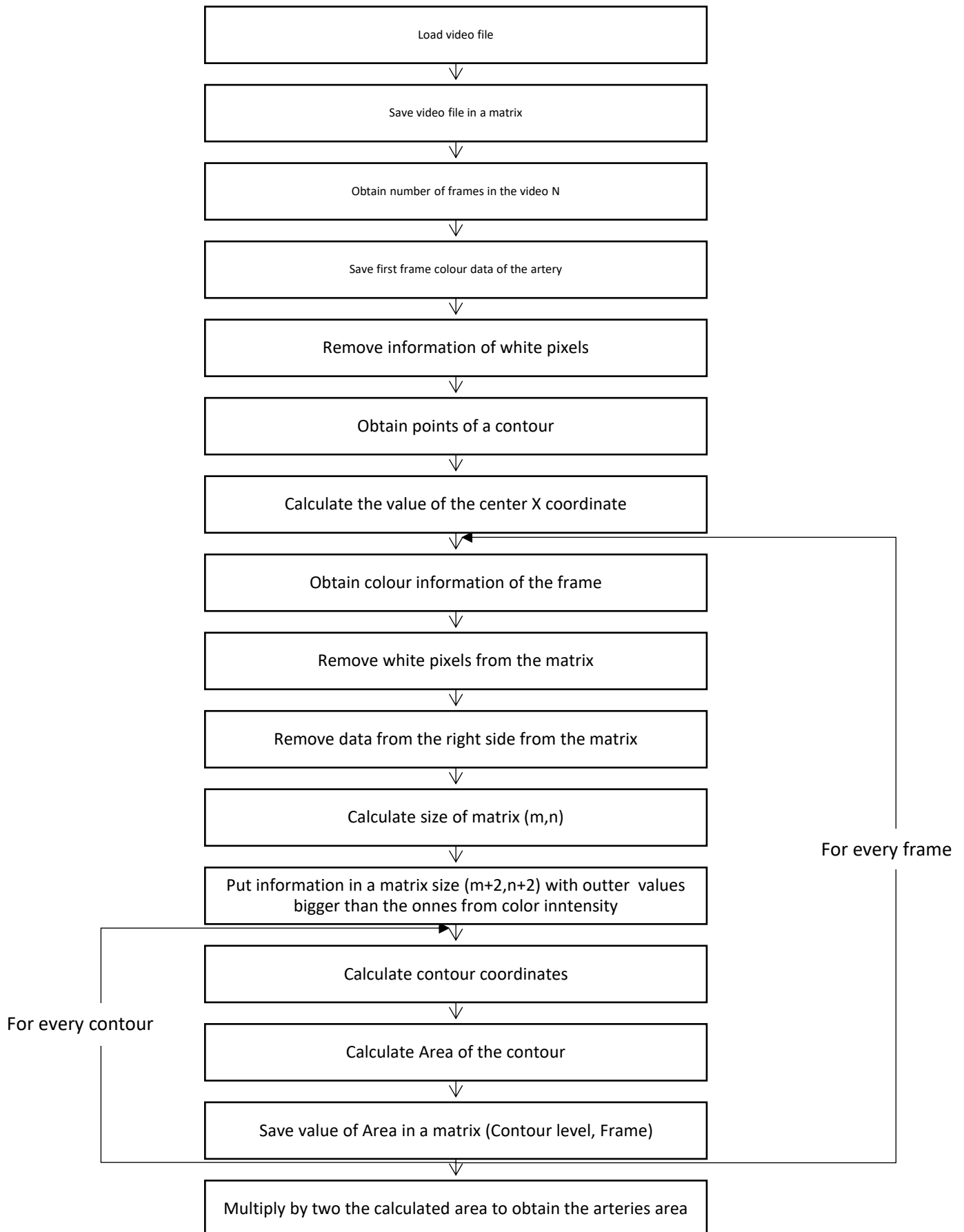
The method proposed to determine changes in the area of the artery is capable of providing a continuous output of data that has the same wave form as the cardiac output (as expected). It can also detect small changes generated by breathing in the area of the artery, which as mentioned earlier produces small variations in the amount of blood that leaves the left ventricle.

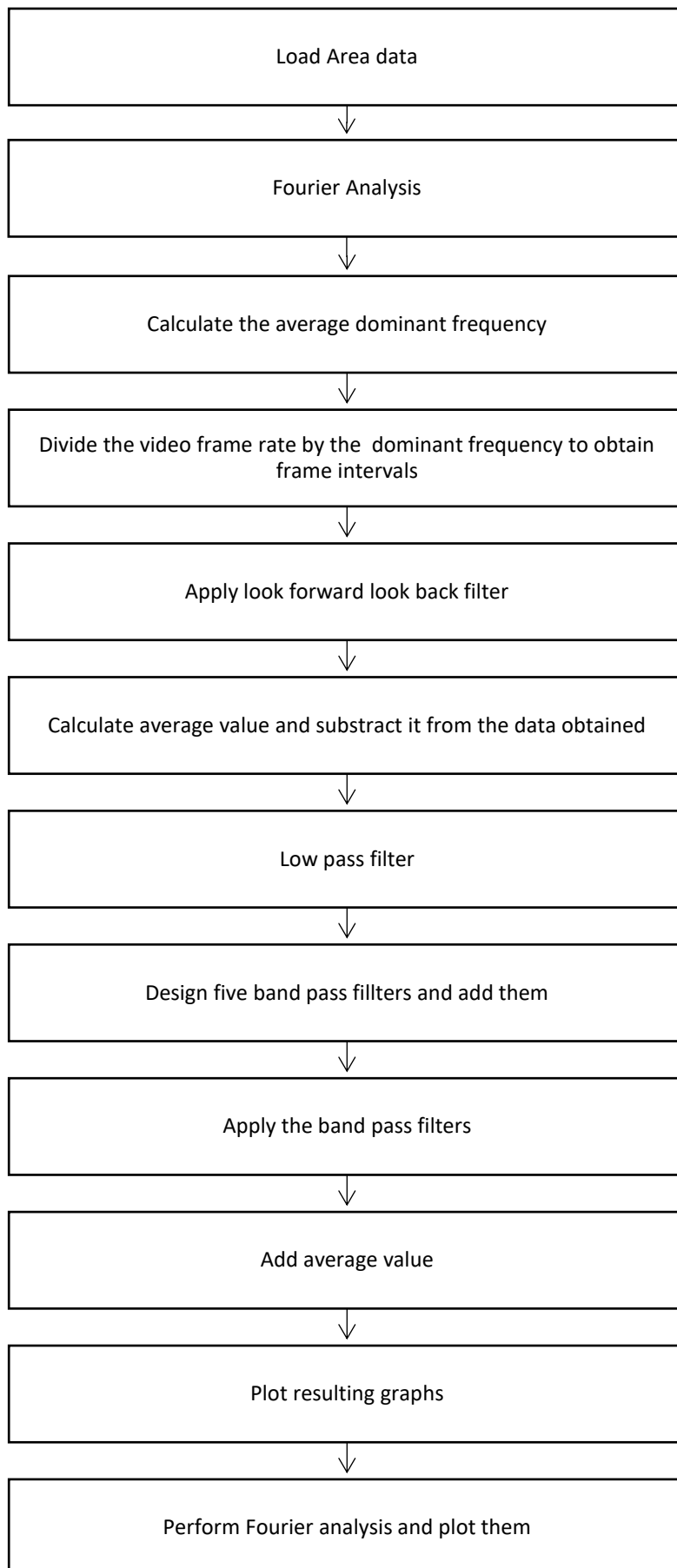
The measurements provided from the analysis of the ultrasound video seem to provide valid information in most of the occasions. The method proposed is especially precise when determining the changes in the amplitude of the area change. The solution proposed was also capable of correctly determining the evolution of the average area in most of the videos analysed.

Improvement can also be achieved if certain changes could be introduced. One of them would be being able to access the scale that the ultrasound equipment uses, this would allow us to provide units with are measurements which can be helpful when determining other cardiovascular properties from the data obtained. Other changes that could be introduced are changing the format of the video output to remove the white line that goes across it and maybe using higher precision equipment to be able to extract more information of the area studied.

## **5. Annexes**

## Annex A: Code diagrams









## Annex B: Code to calculate the area of the artery

```
% Load video
% we will first load the video and extract some
parameter from it

v = VideoReader('201801251340530024SMP.mp4');

vidWidth = v.Width;
vidHeight = v.Height;

%Then the video information will be loaded to a
variable that will help us operate

video = read(v);

%the length of the video will be calculated by
obtaining the number of
%frames

L=length(video(1,1,1,:));

%Then the coordinates of where the artery is will be
saved

x1=466+15;
y1=180+8;
x2=522+15;
y2=215+8;

% The first frame will be used to calculate the centre
of the artery so the right side can be removed

I=video(y1:y2,x1:x2, 1,1);

% The information of the pixels in the white line will
be removed

I(:,25:26)=[];

% The coordinates of a contour will be calculated

C=contour(I,[40 40]);

%Knowing the coordinates of the points in the contour
we proceed to calculate the centre
```

```

sum=0;
denominator=0;
for i=1:length(C(1,:))
if (C(1,i)<=56)
    sum=sum+C(1,i);
    denominator=denominator+1;
end
end
centre=sum/denominator;

% As the coordinates are natural numbers the decimal
places are removed

centre=fix(centre);

%% Area calculation
% 16 different level curves will be calculated for
each frame

for j=10:10:160
for b=1:L
I=video(y1:y2,x1:x2, 1,b);

% The white line is removed first

I(:,25:26)=[];

% Then the the information from the right side is
removed from the matrix

J=I(:,1:center);

%The size of the final matrix is calculated

[m,n] = size(J);

% A new matrix is created where the previous matrix
will be included this
% is done to close some boundaries in higher level
curves

K=1000*ones(m+2,n+2);
K(2:m+1,2:n+1)=J;

% For every frame different level curves are
calculated

```

```

for j=10:10:160

% The level curve is calculated

C=contour(K,[j j]);

% The code that provides the coordinates sometimes
gives coordinates that are out of our plane, so those
will be removed

[f,g] = size(C);
P=1.1*ones(f,g);
s=1;
for i=1:g
if (C(1,i)<56)
    P(:,s)=C(:,i);
    s=s+1;
end

end

P=P(:,1:s-1);

%Then the Area is calculated

F(j/10,b)=polyarea(P(1,:),P(2,:));

end
end

%The final area obtained is multiplied by two to
obtain the whole area

F=2*F;

%The final data is saved

save('Data201801251340530024',F);

```



## Annex C: Code to filter the raw data

```
%Before running this program the data output is loaded  
from the program used to calculate the area
```

```
load('Data201801251340530024')
```

```
% First a Fourier analysis will be done to find the  
most dominant frequencies
```

```
l=length(F(1,:));  
t = 0:1/10:(l-1)*1/10;  
fList = 10/l:10/l:10;  
figure  
for m = 1:16,  
    subplot(4,4,m)  
    y(:,m) = fft(F(m,:))-mean(F(m,:));%The average  
value has been removed to make the fft easier to read  
as the 0 HZ component is too high  
    plot(fList, abs(y(:,m)/l))
```

```
    %We will now proceed to find the frequency that  
    has the biggest magnitude
```

```
    a=find(fList>0.2,1);  
    [e,r]=max(abs(y(a:(length(fList)/2),m)/l));  
    freq(m)=fList(a+r-1);
```

```
end
```

```
% After the most relevant frequencies are found the  
frame intervals for the look forward look back filter  
is calculated
```

```
interval=10/mean(freq);
```

There will be two cases when applying the look forward look back filter: 1) The frame interval is an integer. 2) The frame interval is not an integer, when the resulting frame interval is not an integer a combination of two frame intervals will be used

```
[m,n]=size(F);  
if(interval==fix(interval))
```

```
% If the resulting interval is a natural number
```

```
    for j=1:1:m
```

```

for i=1:1:n
    den=1;
    num=F(j,i);
    if(i-2*interval>0)
        den=den+1;
        num=num+F(j,i-2*interval);
    end
    if(i-1*interval>0)
        den=den+1;
        num=num+F(j,i-1*interval);
    end
    if(i+1*interval<n)
        den=den+1;
        num=num+F(j,i+1*interval);
    end
    if(i+2*interval<n)
        den=den+1;
        num=num+F(j,i+2*interval);
    end
    E(j,i)=num/den;
end
end
else
    % If the resulting interval is not a natural
    number a combination of two intervals will be used

    for j=1:1:m
for i=1:1:n
    den=1;
    num=F(j,i);
    if(i-2*fix(interval)>0)
        den=den+1;
        num=num+F(j,i-2*fix(interval));
    end
    if(i-1*fix(interval)>0)
        den=den+1;
        num=num+F(j,i-1*fix(interval));
    end
    if(i+1*fix(interval)<n)
        den=den+1;
        num=num+F(j,i+1*fix(interval));
    end
    if(i+2*fix(interval)<n)
        den=den+1;
        num=num+F(j,i+2*fix(interval));
    end
    if(i-2*(fix(interval)+1)>0)

```

```

        den=den+1;
        num=num+F(j,i-2*(fix(interval)+1));
    end
    if(i-1*(fix(interval)+1)>0)
        den=den+1;
        num=num+F(j,i-1*(fix(interval)+1));
    end
    if(i+1*(fix(interval)+1)<n)
        den=den+1;
        num=num+F(j,i+1*(fix(interval)+1));
    end
    if(i+2*(fix(interval)+1)<n)
        den=den+1;
        num=num+F(j,i+2*(fix(interval)+1));
    end
    E(j,i)=num/den;
end
end
end

% The mean area is calculated before any filter starts
as they will remove
% or damp the continuous component. Then tis average
values will be added
% to the final result

for m = 1:16
    average(m)=mean(E(m,:));
    for i=1:1:l
        F(m,i)=E(m,i)-average(m);
    end
end

% Low pass filter. Frequencies higher than 10Hz are
removed

plot(t,F)
wLPF = 10*2*pi;
sysLPF = tf(wLPF, [1 wLPF])*tf(wLPF, [1 wLPF]);
figure
for m = 1:16
    subplot(4,4,m)
    FLPF(m,:) = lsim(sysLPF,F(m,:),t);
    plot(t, FLPF(m,:))
end

```



```
%The five band pass filters are built. A band of 0.2Hz  
will be allowed to  
%pass
```

```
q=mean(freq)
```

```
%First band pass
```

```
FH1=q+0.1;  
FL1=q-0.1;  
F1=sqrt(FH1*FL1);  
Q1=F1/(FH1-FL1);  
w1=F1*(2*pi());  
sys1=tf([w1/Q1 0],[1 w1/Q1 w1^2]);
```

```
%Second band pass
```

```
FH2=2*q+0.1;  
FL2=2*q-0.1;  
F2=sqrt(FH2*FL2);  
Q2=F2/(FH2-FL2);  
w2=F2*(2*pi());  
sys2=tf([w2/Q2 0],[1 w2/Q2 w2^2]);
```

```
%Third band pass
```

```
FH3=3*q+0.1;  
FL3=3*q-0.1;  
F3=sqrt(FH3*FL3);  
Q3=F3/(FH3-FL3);  
w3=F3*(2*pi());  
sys3=tf([w3/Q3 0],[1 w3/Q3 w3^2]);
```

```
%Fourth band pass
```

```
FH4=4*q+0.1;  
FL4=4*q-0.1;  
F4=sqrt(FH4*FL4);  
Q4=F4/(FH4-FL4);  
w4=F4*(2*pi());  
sys4=tf([w4/Q4 0],[1 w4/Q4 w4^2]);
```

```
%Fifth band pass
```

```
FH5=5*q+0.1;  
FL5=5*q-0.1;  
F5=sqrt(FH5*FL5);
```

```

Q5=F5/(FH5-FL5);
w5=F5*(2*pi());
sys5=tf([w5/Q5 0],[1 w5/Q5 w5^2]);

%The filters are added

sum=sys1+sys2+sys3+sys4+sys5;

%Data filtration

figure
for m = 1:16
    subplot(4,4,m)
    A1(m,:) = lsim(sum,F(m,:),t);

    %The mean values are added and the resulting data
    is plotted

    A1(m,:)=A1(m,)+average(m)*ones(1,1);
    plot(t, A1(m,:))
end

%A final Fourier analysis is performed to observe the
results

figure
for m = 1:16
    subplot(4,4,m)
    y(:,m) = fft(A1(m,:)-mean(F(m,:)));

    %The average value has been removed to make the fft
    easier to read as the 0 HZ component is too high

    plot(fList, abs(y(:,m)/1))

end

```



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