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**Sudhakar Mishra**

**Abstract:**

In this work, we implemented an unobtrusive and non-invasive method to measure pulse rate and heart rate variability. We used Ballistocardiography technique which describes ballistic force applied by heart on blood. Ballistocardiography depicts repetitive motion in human body against blood flow because of the ballistic force. I followed process in which we recorded a video to capture this repetitive motion in head. I localized face in video frame and extracted features. These features are tracked using Lucas - Kanade point tracker and resultant trajectories is processed with high-pass filter to filter out noise (Unwanted signal). Filtered signals are analyzed with PCA to get component corresponding to motion due to pulse. Component is selected based on analysis of dominated frequency in power spectrum of projected signal. Then I detected Beat in the signal and calculated Heart Rate Variability. We tested this algorithm with 11 subjects (10 males and 1 females) and recorded 14 samples with variation in skin color , sex, subject's state and frame resolution. We found that user state and behavior affects Heart Rate variability.

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**Section 1: Introduction:**

In this thesis, I extracted pulse rate and Heart rate variability parameters by processing video, framing human head. I proposed and implemented an non-invasive and contactless old technique called "Ballistocardiography" which underlies Newton's third law of motion and describes ballistic force applied by heart on blood to flow throughout the body.

**1.1 Motivation:**

1.I read a report made available on internet by World Health Organization in 2013 [133] about death statistics due to Cardiovascular diseases. Statistic is horrific and informing that in 2008 around the globe 17.3 million people died because of cardiovascular diseases and it is predicted that by 2030 CVD will be relatively single cause of death. Report given by WHO is suggesting that low and middle income countries are affected more than Rich countries. Report also suggest that poorest people are affected most in these countries, because of catastrophic health spending and high cost. Along with other risk factors like Tobacco, unhealthy diet etc., lack of medical facility is also an big issue. GDP of these countries is also affected because of Premature deaths of citizens at their productive stage. Lack of facility for early detection is a major risk factor of deaths whereas heavy cost for treatment because of late detection is result of it. Early detection remove the requirement of rigorous medical attention and medicines ,consequently, less Burdon of treatment. Due to lack of primary health care facilities, people in these countries ignore symptoms related to CVD. Medical facilities are unreachable by normal low income and unaware citizens, because these are very costly affairs for a low and middle class families. Medical setup that these devices are required create a panic among unaware people in rural areas like ECG electrode setup (White Coat Syndrome). In India medical devices which are basically needed are rarely available in villages. People in rural areas are not used to about using these devices. They are mostly available in town and cities. Despite of device availability in cities usually people don't prefer to go to clinic because doctor or pathologist charges heavy service fee. Availability of medical services with low cost and reachable to every individual can down WHO projection and help to control this leading cause of death. To make it possible Net cost of device should be less, use of it should not required any specialist to assist and it should be available to everyone easily either publicly (Like in Public places) or individually (ubiquitous).

2. Damage and skin irritation for new - born baby and old age persons due to liquid and electrode placements.

3. Medical science have sophisticated technologies to measure heart health but still science is limited in case of physiological measurement of severely burn patient. If there is no place to put electrodes on body, doctors has to invade catheter in arteries. Due to edema interference, measuring blood pressure is difficult task.

These reasons compelled me to think about providing a different cost effective and approachable solution to measure heart related important parameters which can be used as a preliminary information for further diagnosis and require no expertise.

**1.2 Problem Definition:**

There is a need to develop a new technique which is simple, comfortable, unobtrusive, non - invasive, and ubiquitous to measure parameters associated with human heart and vascular system.

**1.3 Objective:**

* The goal of this thesis work is to develop contact-less , cable less , non-invasive and simple technique to measure important heart related parameters Pulse Rate and Heart Rate Variability
* The technique should record pulse rate and Heart Rate Variability using head vibrations in video.
* Technique should be simple to use and require no expert.
* Technique should be able to capture variation in pulse rate for different - different user states.
* Technique should be comfortable enough to be used for long term monitoring.
* Technique should work even when face is not visible so that it can be used in cases when subject is wearing mask/severely burnt.

**1.4 Introduction and comparison among different trends to measure physiological signals**

Table 1.1 Comparison of Different Cardiac Monitoring Techniques

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Questions** | **ECG** | **PPG** | **Holter Monitor** | **BCG** |
| Definition | Record of electrical activity of heart. | Record of change in volume of blood in micro-vascular bed of tissue. | Record of electrical activity of heart. | Record Ballistic force applied by heart to blood |
| How it works | Electrical impulse generated by SA node flow from top to bottom of the heart causing contraction and relaxation of heart chambers and this activity is captured by spotted electrodes | Organ is illuminated with light, emitted from LED and reflected light is recorded by photodiode receptors. | It works same as ECG with less number of electrodes. | Underlies Newton's third law of motion. Body moves while reacting to blood flow due to this ballistic force. |
| Setup | Patient has to put off cloths and sites of electrodes has to be hair less and clean. ECG gel is applied and electrodes are placed on patient's chest and limbs. | A device has to be clipped on finger tip or attached at ear-lobe or forehead to get change in blood volume. | Setup is same as ECG where electrodes are to be placed on chest only not on limbs. | No setup, all patient has to do is lay down on bed or sit on chair in case of early BCG. Modern BCG is more compact and comfortable. |
| Predicts | Abnormal Heart Rhythm (Arrhythmia), coronary artery disease, Birth defects of heart, heart valve disorders, inflammation of the heart, Enlargement of the heart, Pulse Rate,  Hear Rate Variability. | Arterial Stiffness,  Hear Rate Variability,  Pulse Rate,  oxygen saturation, blood pressure and cardiac output, assessing autonomic function and also detecting peripheral vascular disease | Abnormal Heart Rhythm (Arrhythmia),  Coronary artery disease, Heart valve disorder, cardiac output, Heart Rate variability, Pulse Rate. | Carotid artery disease in conjunction with ECG can replace ultrasound of carotid artery,  Pulse Rate , Heart Rate Variability. |
| Doctor's Point of view | ECG is most reliable tool for doctors other than any device for getting heart status | Not reliable than ECG | Reliable | Not Reliable till now |
| Patient's point of view | Patients dislike it since electrodes placement requires irritating setup. | Easy to use and require no expert, but clip may be painful. | Patients feel restriction after putting electrodes on chest as he/she cannot take bath or wet it. | Good. As it is not required any co-operation from patient, all patient has to do is sit or lay down idle. |
| Patient with fragile skin (New born and old age) | Not good for New-born baby and old age person because ECG gel causing skin damage or irritation. | Because of the clip it is not good for new-born babies and old age persons. | Not good, reason is same as for ECG. | Good for monitoring of patients with fragile skin as it doesn't require any contact with body. |
| Severely Burnt Patients | Not applicable for severely burnt patient if electrode site is burnt. In place of it catheter is used. | May be useful if site is not burnt.  (Site: Forehead, Ear lobe, Finger Tip) | Not applicable | Good |
| Wearable and Long-Term Monitoring | Only for Short term Monitoring. (Usually 10 seconds) and not wearable. | It may be used for Long-Term Monitoring and wearable but clip may cause pain. | It is used for long-term monitoring but ECG gel cause skin irritation. It is wearable device. | Yes and can be used for long-term monitoring. |
| Software or interface assessment | Not good, because it needs contact with human body. | Not good, because it requires direct contact with organ | Not good because it needs direct contact with human body. | Yes |
| Contactless | No | No | No. | Both |
| Cable-less | No | Possible | Possible | Yes |
| Need of Expert | Yes | No | Yes | No |
| Limitations | Short Time (may not reflect sever underlying heart problem)  Not self-sufficient, occasionally require other cardiac test like Echocardiogram , Exercise stress test[194]  White - Coat Syndrome,  Skin irritation,  obtrusive | Limited information,  Obtrusive  (Information: Heart Rate and Cardiac cycle, Respiration, depth of anesthesia, Hypo- and hypervolemia.) | Require expert to set up monitor,  Impose restriction on patients for some activities,  Need to clean and shave site otherwise poor contact may leads to poor recording,  Too much movement cause detachment of electrodes | Limited information,  Not reliable in clinical environment |
| Advantages | Most reliable during emergency or surgery | No White - coat Syndrome | Long - term monitoring, True heart condition, White Coat Syndrome. | Long - Term Monitoring, Comfortable, No White coat syndrome,  Unobtrusive |

**1.5 Background and Technique:**

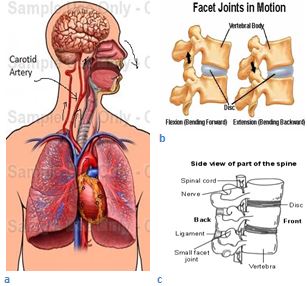


Figure 1.1 a) Ventricular Contraction Blood flow and eventually head motion [195] b) Facet joint in motion [196] c) Discs Stack Organization [197]

In this project I used an old technique called Ballistocardiography which was first acknowledged by Gordon in 1877, letter described in more detail by Starr in 1939. With the advanced tools of the 21st century in the field of signal processing, human sensor's simulation techniques, hardware technology and increasing demand of e-home systems and unobtrusive computing given reason to again develop this technique.

Task force of some U.K. based researchers presented a concept that pulsation causes vibration in head, Which can be captured by camera. Principal behind this vibration is "Newtonian's third law" which states that action is equal to reaction. Heart applies ballistic force to blood when it contracts and generates blood flow against arterial wall. A force is applied to arterial wall by blood flow, consequently wall of these arteries expands from its normal size. After passing blood arteries wall restores its original size. Since face has enough arteries which collectively gives movement to head. Due to pulse arrival head moves in downward direction as shown in figure 1.1(a). Movement in head due to pulsation is corrupted by cervical discs in head-neck joint. These Discs are arranged in stack form and each disc has analogy with spring fixed at both the ends. This stack organization is supported by facet joints which provide stability and movement as shown in figure 1.1 (b) and (c). Vibration in head is created due to concept called Dynamic equilibrium which says "Net force on mechanical system is zero". Two equal and opposite forces called displacement force and restoring force applies on discs and creates vibration in head. Net acceleration due to which head moves calculated by D.D.He. [131] is 0.98 mG(≈0.098 m/s2). Using the following equation

Displacement =

calculated displacement of head is = ≈ 5 mm.

Where second is ventricular ejection time. This displacement is very small to track.

I recorded a video of human face using camera. Although this movement is very small so precautions has to be taken while recording this video. Light source should be constant, subject should sit ideal while recording is going on. With these constraints I am recording video of a human face. Face detector is applied to detect face in frame. There is vibration in face so I need to have some feature points. These feature points are tracked using point tracker which is working on the concept of optical flow. Along with information related to pulse resultant trajectory of these feature points, also has other movements which is noise and need to be filtered. A high pass butter-worth filter is applied to pass frequencies require to recover pulse information from noisy signal. Component analyzer is used to extract a component corresponds to pulse. Finally beat locations are localized to get information about time of beat and Heart rate variability is calculated.

**1.6 Output parameters (What are these and how are they regulated by CVD)**

Two Output Parameters:

* *Pulse rate*: Pulse is generated due to blood vessels' wall resistance against blood flow. Each cardiac cycle push blood to these arteries, consequently pulse is generated. Pulse rate is "number of pulses per unit time". Pulse rate is very important parameter. Pulse rate is usually considered equivalent to heart rate by medical practitioners for cases where subject is not exposed to bad heart condition which is restricting blood flow. Pulse rate differs from heart rate when heart is not pushing blood properly (Its muscles got weak) but it is "Depolarizing and Re-polarizing" i.e. beating.
* *Heart rate variability*: Heart rate variability is an useful parameter. By definition it is a measure of variation in beat to beat interval. It can give fruitful results if it is measured for long time. Heart rate variability (HRV) leads to predict many cardiac events and gives information about "Sympathetic and parasympathetic autonomic nervous system"."Sympathetic and parasympathetic autonomic nervous system" are directly connected to "Heart" and "Lungs" through fibers. It controls "Heart rate" as well as.

"Respiration rate". Figure 1.2 showing flow of "supply-demand" relationship between heart, ANS and requirement of body.

Cells and Tissues send signal to ANS, asking for Oxygen and nutrients

ANS send signal to heart and stimulate SA node for generating impulse

cells and tissues are getting enough nutrients

No

Yes

Increase heart rhythm

Normal heart Rhythm

Figure 1.2 Nervous System and Heart Rhythm

*Clinical application of Pulse Rate:* Pulse rate is analogous to heart rate.

*Clinical application of HRV*: Deep analysis of "Heart rate variability" by doctor can lead to information about malfunctioning of Autonomic control system, because "Sympathetic and Parasympathetic nervous system" regulates heart rate by controlling Sinoatrial node, whereas SA node keeps command on heart rhythm. Researchers are studying and trying to draw some conclusion for relationship between "Pulse rate variability" and "Cardiovascular diseases". Irregular heart beat leads to irregular palpitation. Irregular palpitation can inform doctors about cardiac arrhythmia and forecast about Heart attack or failure. Although still at this stage there is not perfect univocal relationship between values of this parameter and CAD.

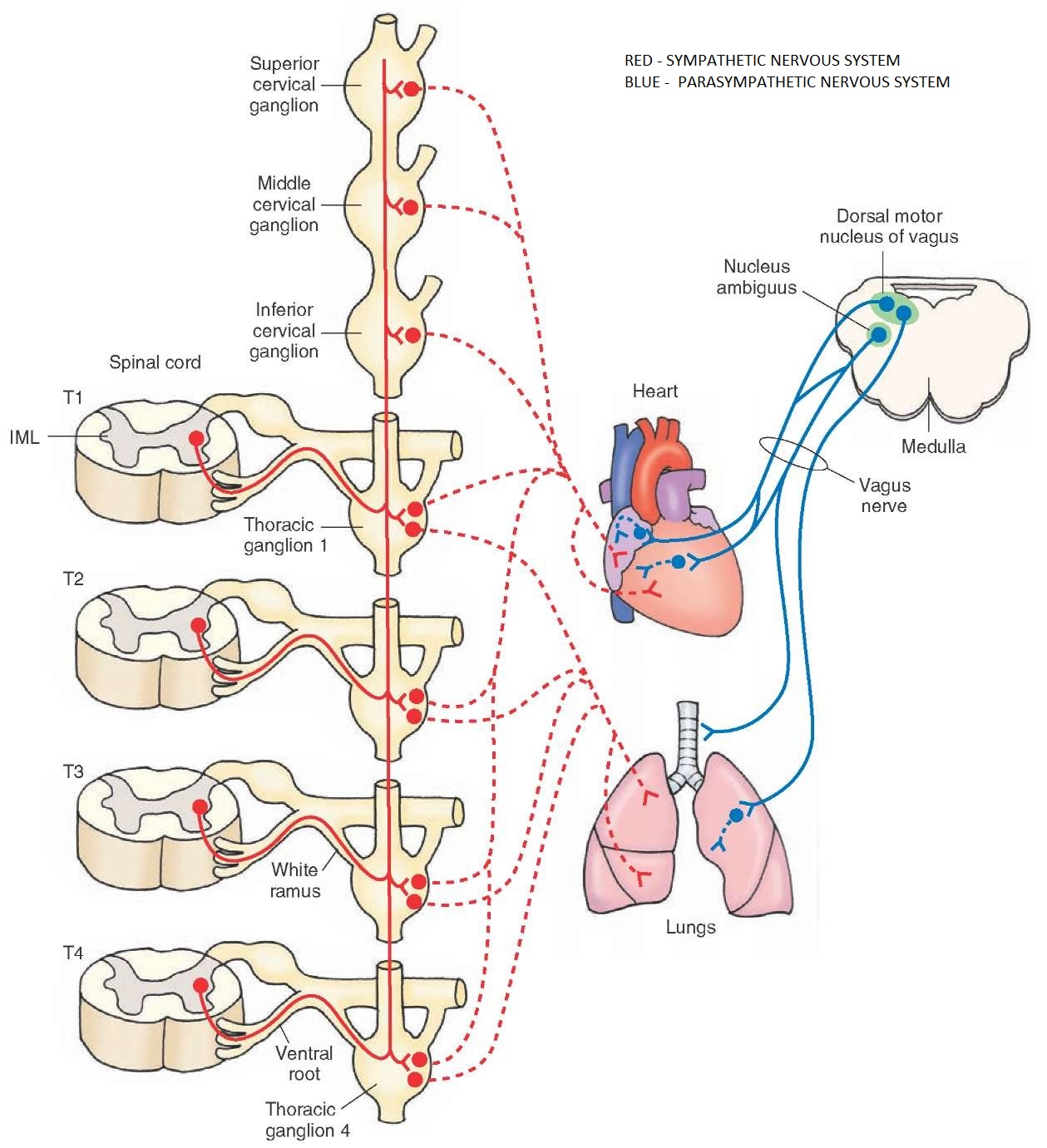


Figure 1.3 Connection of SA node, Heart chambers with Sympathetic and Parasympathetic Nervous System [198]

Heart Rate Variability got attention by researchers because of its importance and simplicity of derivation. Figure 1.3 is showing clear connection between "Sympathetic and parasympathetic nervous system" and "heart's chambers" and "pacemakers". So there is a clear relationship among "Autonomic nervous system" and Heart rate variability, cardiovascular diseases [187]. Heart rate variability (HRV) in different-2 states like "Resting", "Running", "Stress", "Standing" can give important information to forecast many "Cardiovascular disease" like "Coronary Artery Disease", "Congestive heart failure", "Cardiac Arrhythmia", "Angina Pectoris", "Myocardial infarction". Long - term monitoring can give more information than instantaneous measurement.

**1.7 Future Applications:**

* Software or Interface assessment for HCI applications
* CVD Prediction
* Human state and emotion prediction
* Covertly Lie detection
* Can be one of model input in Video Surveillance along with other inputs like activity.
* Severely Burnt patient monitoring
* New born baby and old aged person monitoring
* Tele-monitoring without clinical environment.
* Long Term Monitoring

**1.8 Summary:**

This chapter described shortcomings in medical technologies. They are unavailable, complex, obtrusive and require clinical environment. A new technique is proposed to rid of these shortcomings. Objectives which we are going to achieve in this work is described. A good comparison between among different trends is described. Possible future applications are also described.

**2. Literature Survey :**

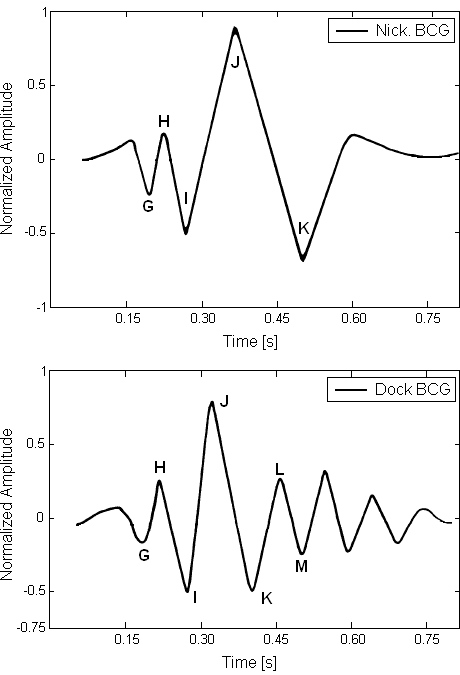
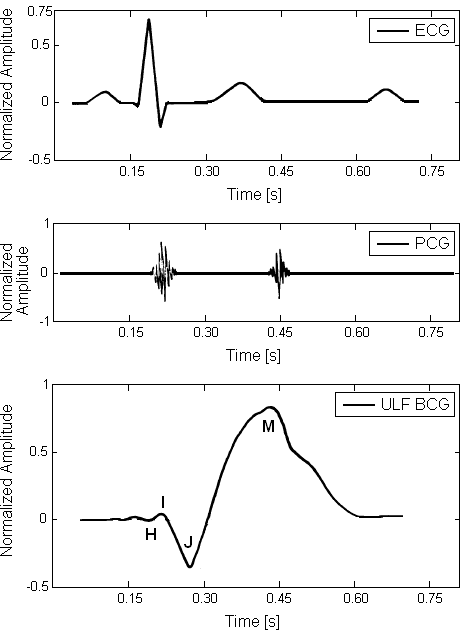
**2.1 Overview :**

Ballistocardiography originally derived from the Greek (*βáλλω* (*ballō*) “throw” + καρδία (*kardia*) “heart” + γραφία(*graphia*) “description”) is a method for describing ballistic force applied by heart ventricles to blood causing repetitive movements of human body. Body moves against the mass of blood flow in every cycle i.e. if blood flows through descending aorta body moves head-ward and at the time of pre-ejection body moves foot-ward. Ballistocardiography gives information about circulatory physiology, "Hemodynamic events" like cardiac volume, blood pressure etc. Every Systolic operation causes mass movement of body not only due to blood flow but also mass of heart itself contributes and circulatory performance information can be obtained by recording of this body movement [1-3]. Since 1877 when Gordon introduced and did pioneering work in this field a lot of versions in the name of improvement came out of the box. In the years of early development of this technique, mid XX century is called golden age of Ballistocardiography because it witnessed various concepts like "High Frequency Ballistocardiography" [1], "Low Frequency Ballistocardiography [2]", "Ultra-Low Frequency Ballistocardiography" [3, 4, 5,6,7,8,9], "Direct-Body Ballistocardiography" [10,11,12,13,14].

Ballistocardiography got attention for improvement so that measurements by this technique can be closely correlated with existing good techniques. Need of this improvement raised from the fact of increasing demographic figures and health care unavailability to every individual [71].

**2.2 BCG Waves:**

In 1956 committee on Ballistocardiographic terminology decided to characterize methods and give a nomenclature to BCG signal. Committee presented Scarborough-Talbot report [48] characterizing devices in those days in 4 category and these category are made based on output waveforms each device produce. First category was "High frequency" and Starr's device managed to get this category. Second category was "Low frequency", characterized Nickerson's device. "Ultra low frequency " or "Aperiodic" was third category and categorized devices by Talbot [11], Rappaport [14], Gordon [4], Henderson [5], Burger[12], Von Wittern [10] and last category was "Direct body" and classified Walker[17], Dock[19], Arbeit[16], Smith[15]. Committee also took decision to describe signal as done by Starr et. al. (8). Starr outlined signal with 9 English capital letters 'G' through 'O'. Every letter is categorizing different-2 activity of heart and cardiovascular system. An Opulent comparison were made between Ballistocardiography and then existing techniques like Electrocardiogram, Phonocardiogram etc as shown by graphs in figure 2.1.



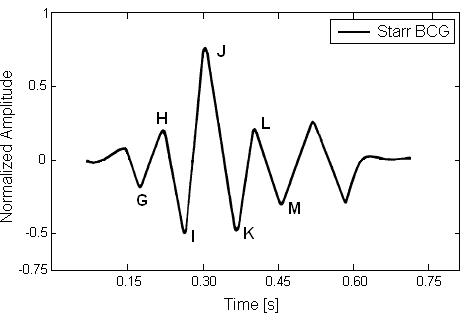


Figure 2.1 ECG Signal, PCG signal and all four category of waveform based on devices. There is a difference in timing of occurrence of peak and waveform itself [48].



Figure 2.2: ECG, BCG from Carotid Artery, Acceleration BCG , Velocity BCG and Displacement BCG

Apart from the Nomenclature with capital letters 'G' through 'O', waveform categorized in groups, the Pre-systolic group, the Systolic group, the diastolic group.

Pre-Systolic Group:

* F Wave: Wave describes Pre-Systolic event has head ward direction and highly disregarded because after vibration it cannot be seen.
* G Wave: This waves has foot ward direction and generated because of body's reaction to previous wave.

Systolic Group:

* H Wave: H wave occurrence is very closed occurrence of 'R wave' which indicates start of ejection. Direction of 'H Wave' is head ward.
* I Wave: It specifies early systole and has foot ward deflection.
* J Wave: J wave occur late in Systole and has Head ward direction.
* K Wave: End of Systole and has foot ward direction.

Diastolic Waves:

* L, N and M Waves: These waves describes diastolic operation and has alternative deflection as shown in figure 2.1.

In 1957 Using the seismometers' horizontal pendulum concept an ultra low frequency device is designed to get greater detail of BCG waves [76]. This report was significant in terms of detail as well as technique of observation called "multiplicity of points ". This observation utilized different segments of wave by decomposing it and reported first time change in H and J waves after respiration is halted, with normal subject.

**2.3 Abnormal Ballistocardiograph:**

Starr in 1939 [8] written a technical report in which he was estimating "Cardiac output", "Velocity of ejection" and "Cardiac force" based on the amplitude of Ballistocardiographic waves. Flick assessed by his method [83,84,85] amplitude of ejection wave in BCG was quit higher than the actual output in case of shock feeling.

Study done by Franco's [78] was based on normal individuals whereas Moser [34] did significant study to find correspondence between BCG and "Myocardial infarction" and cross checked with ECG ground truth. He involved 100 subjects in his study. All were recovered from "Myocardial infarction". In his study he got 81 abnormal and 19 normal Ballistocardiograms.ECG detected 74 subjects of 81 registered abnormal in case of BCG. But difference lied in case of normal BCG where ECG detected 17 out of 19 cases registered normal by BCG.

Study by Gubner et.al. [3] and I. Starr and F.C. wood [106] concluded that Abnormal BCG prognosticate future complications in case of "Myocardial Infarction", "Angina Pectoris" and "Asymptomatic Coronary Artery Disease" specially for elders.

Dock [108] and Scarborough [109] did study with 152 and 191angina patients respectively. Percentage of abnormal Ballistocardiography were 92% of 152 and 75.4% of 191, with one more observation of increment in incidence with older age.

Next observation which researchers has to make with BCG was related to Drug's effect in Ballistocardiography. Starr [87] and Nickerson [74] did excellent job for pharmaceutical field by observing effect of Drug in BCG. They reported alteration of BCG because of following agents: Nicotine [92 , 93], Quinidine [89], Sympatholytic Agents [38], Nitroglycerin, among other nitrites [91], Digitalis [88], Epinephrine [90], Visammin [90].

Nicotine intake alters the BCG signal, studied by Davis et.al. [73]. After smoking patients with "Coronary Vessel Disease" observed. These patients were resulting deformed Ballistocardiogram because of nicotine effect [92 , 93].

*2.3.1 Age Factor:*

Several studies on numerous groups [26, 36, 77,78,79,80,81] demonstrated age factor on a priori behind abnormal BCG patterns. Franco's[78] experiment conducted on 371 subjects (Normal i.e. no cardiovascular disease) where he got 50% abnormal BCG cases with age range from 35 to 64, interpreted as forecast of development of disease. Studies done by Franco and other researchers in twenty one years after breakthrough given by Starr in the field, crowned quantitative importance to Ballistocardiography [82]. Remark for BCG in Quotes is made by Follow-up researches : “*(…) Hearts contracting with little force at the initial test later suffered from death and cardiac disability, chiefly coronary heart disease, in far greater numbers than those whose hearts contracted strongly. The amplitudes of Ballistocardiograms, strongly correlated with the later development of heart disease and also strongly correlated with the ages of the subjects".*

Above study suggests that heart of subject having myocardial disease works as heart of older age one works i.e. "Physiological age" of heart can be different from "Chronological age" of subject and prognosticates heart disease in future. Regardless of patient's age using BCG future of heart's health in terms of "Coronary artery disease" can be presaged."

**2.4 Disease effect on Waves:**

Correspondence between disease and BCG is not univocal. Gubner et.al.[3] established an analogy between abnormal Ballistocardiography and Heart valves' Malfunctioning. His research also contributed to early failure of myocardial function. He found that narrowing valves does modify amplitude of Ballistocardiogram. Mitral steno sis and Aortic steno sis decrease and increase amplitude of I and J waves respectively.

Diminishing K wave confirms case of "Coarctation" [25, 29, 30, 94].Researchers found that "Coarctation" of the aorta can be prognosticated with the Ballistocardigram.

Donoso et.al. [94]and I. Starr [95] also analyzed K wave. They explained diminishing K wave as indicative of "Patent ductus arteriosus", "Eisenmenger’s complex", "Hypertension" , "Arteriosclerosis".

**2.5 Technique and Device Development:**

Ballistocardiography again got attention with 21st century tools. Although advanced tools in the field of hardware as well as software given new dimension to the field but still it shares common ground with earlier BCG implementations. Hundred of research papers published in the early stage of its development which provides strong knowledge for 21st century group.

*2.5.1 Early Development:*

This movement first observed by Gordon who used rigidly supported weighing machine connected with vascular system. Needle movement of weighing machine which impart body movement is interpreted by an delicately adjusted instrument which in turn produces sphygmograph. Rule which Gordon set for his experiment are: with each systolic occurrence needle will deflect towards zero from its original position (original position of needle reflects subject's weight) and in the interval of systolic, needle will try to come to its original position which is indicative of restoring stability [4]. Problem With Gordon's set up was related to posture in which knee joint should be rigidly connected to each other and should make right angle with heap. Any movement during experiment create artifact in result. Another problem was related to connection between vascular system and weighing machine. Figure 2.3 is showing result obtained by Gordon.

****

Figure 2.3Down-stroke corresponds to Systole and following up-stroke is instrument's tendency to restore equilibrium [4].

Yandell Henderson (1905) recorded recoil curves and circulation and Resonance frequencies using a "swinging bed" rigged with springs and set of levers then amplified them [7]. Shortcoming of his experimental setup was, to get heart beat synchronized record subject had to arrest respiration[5]. For 25-30 years nothing was done with this method until Isaac Starr modified this instrument and made available this technique to measure functionality of heart. Because of bulkiness of the equipment, it didn't got much attention for clinical application until Dock and Taubman [18] described a ballistic curve measures directly from the body with instrument which was portable, simple and easy to construct. Douglas et.al. in 1913 presented a simplified form of apparatus as shown in figure 2.4 rubber stoppers are supporting plank [6].

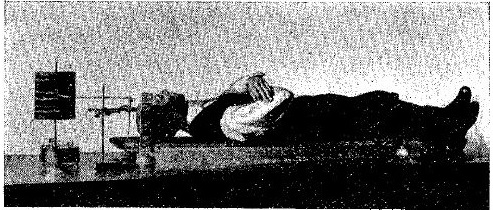


Figure 2.4 Photograph of recoil apparatus with which the curves of BCG were obtained, consists of a plank supported on rubber stoppers. The recording lever magnifies the recoil movement 60 times.

Heald and Tucker (1922) used diaphragm of a drum which has hot wire in its air inlet. There is change in current flowing through hot wire if any movement happens to be in subject's body stood on a Diaphragm suspended platform. Their experimental setup was unable to give direction of movements. Angenheister and Laue (1928) experimented using seismograph attached rigid table. Subject lay down on the table and reading of movements can be recorded by seismograph. Isaac Starr boosted this terminology by continuing high impact discoveries and researches for decades and titled as founding father of this field [6,7,8].Isaac inspired in 1929 by design created by Yandell Henderson and determined to remove flaw in his design by counteracting the minute movements using springs and allowed patients to breathe during recording [7]. Starr designed first device similar to first design which can accurately give physical measurements [7].

Starr developed [9] device which later entitled "High Frequency Ballistocardiograph". With a natural frequency of 9 Hz he developed a "spring-coupled un-damped table". Intelligently he developed his device free of "Baseline Drift" because of high frequency, bad side of his design was filtering some events related to cardiac cycle which creates other form of distortion in BCG waves. In the intention to improve design Nickerson [9] designed his setup with lesser frequency of 1.5 Hz to reduce Ballistocardiographic distortion due to filtering of cardiac cycle event. But unfortunately his design unable to eradicate trade-off between baseline drift and signal modification and he has to compensated with baseline drift. Some technical reports also published question about simultaneous movement of both table and body.

While in consecutive years Nickerson [9] and Hamilton [25] managed to get Ballistocardiographic signals directly from the body, with subject is in supine position, without using suspended table. First time someone used head vertex as their measurement site. Dock and Taubman [18] achieved little bit better by using the subject's shins as measuring site. They used Photoelectric and electromagnetic methods for measuring relative movement. With "Photoelectric sensor" they recorded displacement while other one is used to detect velocity of the body.

Early Ballistocardiographic devices were bulky mainly measuring forces applied in the "Longitudinal axis of the body". Apart from observation in "Longitudinal axis" Brandit et. al. [96] took lateral plane approach and in 1950 "Multidimensional Vector Registration" approach adapted by researchers [97,98,99].Since so many researchers tried hard to make a univocal correspondence between waves and forces but due to three reasons they failed. First, Force projected on the body is not only due to systole but there are is vector sum of forces involved. Second, since coupling channel between body and platform is soft tissues which can suppress enough force. Third, if heart is beating so fast, it is a chance of superimposition of waves.

Early Ballistocardiography development was facing two main problems, first was related to interpretation [2, 3, 20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39] and second was related to interference of vibration in BCG recording [2, 39,40,41,42,43,44,45]. In the age of development of this technique so many researches published and new devices and nomenclatures were presented so defining a standard for designing instrument with some electronic and mechanic restrictions was a difficult task [46,47,48,49]. Then American Heart association instituted some conventions for Ballistocardiographic terminology [48].

Although Ballistocardiography significantly proved itself for cardio-logical examinations in its early face like electrocardiography, fluoroscopy or radiology, but it is failed to be employed in clinical environment because it gives limited information. Some other factors like cost effectiveness, difficulty in deploying in clinical applications were obstacles for its popularity [3]. But In 1953 Gubner given a statement regarding appraisal for this technique as [3]-"*(...) it may be remarked that the ballistocardiogram provides, in simple and routinely applicable fashion, a considerable body of useful information not otherwise obtainable; and hence fulfils the criteria of a valuable adjunct in examination of the heart.*”

Early Ballistocardiography was not that much accurate and popular because lack of advancement in technology and ubiquitous computing. Researchers focused knowledge of then developing analog and digital signal processing to create framework for Ballistocardiography to do physiological studies [58, 61, 69, 70].

During year of progress another improvement in 1950 came up with medical application of "Piezoelectric sensors" by Sheehan's team [100]. This sensor basically transforms pressure into electric charges. Although this sensing material was far better than previous ones but still good result can be ensured only if there is a good coupling between body, table and sensor [44].

With the advancement of signal processing and semiconductor technology Ballistocardiographic technology got rid of various shortcomings like artifacts due to respiration, artifacts due to instruments etc. Technique also got aid from high speed computers for analysis and artifact removal. With the use of "Static Charge Sensitive Bed [54]" and "Body Mould Bed [55]" for signal recording, Ballistocardiographic technique entered into modern era. Extensive use of signal processing, semiconductor terminology and sensors took place. Pervasive application of Electromechanical film (Emfi) and piezoelectric Emfi sensors in the chair, bad, toilet allowed ingraining Ballistocardiography in the environment and expedited long-term evaluation [58,59,60,61,62,63,64,65,66,67,68,69,70].As Technology available with low cast, demand of home e-health system got breakthrough which also raised demand of unobtrusiveness and ubiquitous computing [50,51,52].Characteristic of Ballistocardiography to assess cardiac performance unobtrusively by vibration due to heart operation, matched with the characteristic of Ubiquitous Computing where user feels comfortable during test with reduced examination stress and medical staff [53].

*2.5.2 Modern Development:*

Research community incorporated from various field to again revive, relative abandoned Ballistocardiographic technique. Latest development in Ballistocardiographic techniques backed by 21st century development, and made Ballistocardiography compact than older massive structures like special bed, swinging architectures etc. As the technology advanced other physiological signals like Thermal change , Skin color change got attention other than Ballistocardiography. Compactness acquiesced BCG to be embedded in environment like in office [58,59,60,61] and wheelchairs [62, 101]. These techniques got popularity because of the comfort with the user's point of view and concede to collect signal from seat, armrest, backrest etc. [58,59,60,61,62, 101] as depicted in figure 2.5. Figure 8 shows different graph for different measurement spots. In fact, measurement from seat confirms information about pre-ejection time and ejection time whereas Backrest acknowledges ejection time. Novel methods has been developed in literature of "contact-free technology". This technology has advantage over technology that involves direct contact with human body in the way that Subject feels comfortable and no stress. With the innovation in Imaging technology new algorithms proposed one after another.

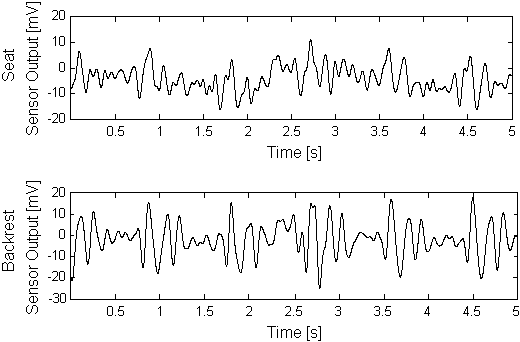


Figure 2.5 Postolache et. al. [101] collected signals from Seat and Backrest.

The basic problem of BCG signal collection is baseline drift [62, 101, 102] which nearly solved by modern analog and digital signal processing, although not completely eradicated. Advanced Signal processing concepts like wavelet decomposition [101], Independent Component Analysis [102] and principal component analysis [103], helped to get information rich signal and filtered out baseline wandering and other components which are source of noise.

*2.5.2.1 Chair Based and optical monitoring Systems:*

Modern chair based systems mainly utilized Electromechanical(Emfi) [56,57] and Piezoelectric Emfi sensors [63,64,65,66,67,68,69,70] because they are less costly, simple in design and use. Because of the current dominated techniques like "Electrocardiography", "Impedance Cardiography", "Plethysmography", Ballistocardiography got relatively less attention ."Need is a mother of discovery" and it is need of ubiquitous and unobtrusive computing which again revived BCG.Figure 2.6 is showing photograph of BCG chair :



Figure 2.6. BCG Chair [58]

If heterogeneous development using different techniques adapted like done by authors [104,105] combined "Digital Photoplethysmography" and sensor embedded chair, then other parameters like "BPV" and "Systolic blood pressure" can also be derived other than primary parameters like "Pulse Transit Time". Apart from unobtrusiveness BCG combined with ECG and Plethysmography can give insightful knowledge about subject's "Cardiovascular Control Mechanism".

Researchers also took advantage of wireless technology along the way of making BCG important technique. Researchers [106,107] used Microwave radar Transducer to transmit and collect BCG signal as shown in figure 2.7 . Transmitter is embedded in chair whereas receiver port is used by Laptop or PC or DAQ system.

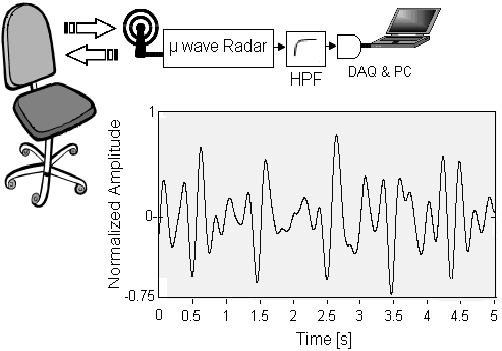


Figure 2.7 Radar BCG System[107]

P. D. Mannheimer and M. E. Fein [128] got a patent for generalizing "Optical monitoring" technology originally developed by Tremper and Kevin K. in 1989 [129]. A Transmitter transmits ray which received by receiver, on the way it passes through any part of body. Receiver receives different frequency waveform modulated by blood

*2.5.2.2 Contact free Technology:*

Digital Technology in medical field delivered a platform where individual can monitor his own health without help of any medical practitioner in day to day life. Digital Technology has ability to produce detailed individual physiological data delicately. Individual person can manage its health related issue with the detailed access and control over its own physiological data. Instead of going to clinic and confronting with "sticky electrodes or wearing chest strip or putting sensors" one can comfortably access detail of its health by standing in front of camera.

Garbey et. al. [127] Used very sensitive thermal imaging camera to capture change in heat of Superior Blood Vessels like carotid artery. Each circulation modulate heat in these vessels. By following line of change they recorded change in heat, which Further processed using FFT to get desired signal of interest. They claimed 88% to 90 % accuracy.

This was the first ever used concept by Ming-Zher Poh et.al. [126] to measure Physiological Signal like "Pulse Rate and Pulse Rate Variability". They used change in skin color with each "Heart-Beat". The Concept is Heart pumps blood when it contracts. Through carotid artery it reaches to network of capillaries in face, then tissue. This Blood circulation change color of face because it contains hemoglobin. Along the way of completing circulation blood flows back to heart using veins. At this stage face restores its normal color. With the next cycle again it is repeated. Using camera researcher recoded the video and applied "Blind Source Separation" technique to separate component exposing Pulse Component. After this Lawandowska et.al. [130] implemented same concept where they selected proper channel and applied principal component analysis. With the excitement of making Device more interactive Ming-Zher Poh et.al.[125] used "LCD monitor and web cam" to design a system where Subject can see himself in LCD turned mirror in sufficient light condition, while at the same time web cam records "Video". After real time analysis with software implemented in Computer, LCD monitor is used to Display "Pulse-Rate". Physiological signal they used is "Change in Skin Color".

With the increasing trend of wearable, ubiquitous and unobtrusive technology BCG became one of the main research focuses. A wearable heart monitor based on BCG and ECG is designed in MIT by David Da He, where 3D accelerometer worn by subject at ear to record motion in head [131].He found relation between R wave (ECG) and analogous J wave (BCG) and derived stroke volume and pre-ejection period parameters. He obtained the BCG signal in three dimensions and derived two conclusions. First conclusion was suggesting that head moves in y axis due to palpitation and second conclusion was suggesting interference of head - neck joint structure in movement. Because of the ventricular depolarization heart applies ballistic force on blood to flow it throughout the body and through Carotid Artery blood flows to head. Blood vessels follow Newton's third law of motion and react to this blood flow. Because of this action by blood flow and reaction by vessel walls head moves. Movement in head due to palpitation is corrupted by cervical discs in head-neck joint. These Discs are arranged in stack form and each disc has analogy with spring fixed at both the ends. This stack organization is supported by facet joints which provide stability and movement. Vibration in head is created due to concept called Dynamic equilibrium which says "Net force on mechanical system is zero". Two equal and opposite forces called displacement force and restoring force applies on discs and create vibration in head. Above two conclusions are utilized by Guha et.al and they captured this vibration in head by recording video of head [132]. Guha measured pulse rate and Heart Rate Variability.

**2.9 Clinical Point of View:**

In literature it is found that BCG is a good indicative of your Heart's age which sometimes different than "Chronological age". Disturbed BCG signal also analyzed in literature for prognosticating heart's contraction related problems.

New clinical knowledge about correspondence between Heart rate variability and blood pressure variability given new thinking direction and interpretation matrix for health measurement. This is also an important factor behind development of BCG, which is different from previous knowledge heart related measurements. With new interpretation which is less concerned about BCG waves interpretation, Blood pressure variability give information about "Autonomic Nervous System" (Sympathetic and Parasympathetic systems) [58, 151, 152, 153]. With the new clinical knowledge BCG expanded to get information about Heart rate and Blood Pressure Variability [61, 154] . True Conclusion can be drawn if observer has long-term reading about parameters which leads to technology that is comfortable, understandable by lay-man.BCG is a good alternative which requires relatively no Medical staff, Sometimes even no physical contact, all subject has to do is sit ideal during examination. Day to examination without any anxiety and irritation can provide actual measurement of pulse rate and pulse rate variability [53].

Heart Rate variability is recognized as a important tool for detecting risk factors of Cardiovascular Diseases as supported by many studies and researches. According to the report of World Health Organization Cardiovascular diseases are major cause of death worldwide [133].Detection and understanding of Risk factors of CVD can help to reduce the death statistics given by WHO in report. Pathological condition of heart can be predicted by Imbalance in autonomic nervous system and there is a clear association between HRV and autonomic nervous system as it regulates pacemaker (Sympathetic branch increase rate of contraction whereas Parasympathetic branch does opposite) and heart chambers according to the requirement of body for blood [134 , 135 , 136 , 137]. Long term monitoring of Heart rate variability (HRV) in different-2 states like Resting, Running, Stress, Standing can give important information to predict Cardiovascular disease like Coronary Artery Disease, Congestive heart failure, Cardiac Arrhythmia, Angina Pectoris, Myocardial infarction [136]. Along with CVD prediction HRV has importance in predicting user's state and behavior. Julian et.al performed a meta-analysis of association of HRV with Amygdala and Medial Prefrontal Cortex. They found that HRV may approximate behavior and health by giving information about "vertical Integration (Integration of three regions Cortex, Brain Stem and limbic area)" of the brain mechanisms that control behavior [138]. Deniel et.al concluded HRV as a novel marker to recognize emotions by finding positive association of HRV with emotion recognition task while experimenting with different age groups [139]. In 1998 an experiment conducted to find relationship between HRV and mental effort. In same experiment user has to play game and simultaneously ECG had recorded. It was found that HRV is affected by mental effort [140]. Studies and experiments summarized above suggesting importance of HRV in diagnosis of cardiovascular diseases, in emotion recognition and in assessing interface friendliness. Traditional way of cardiac monitoring requires physical contact with any part of human body like for ECG, electrodes should be placed at right spot on chest with irritating chemical solution for conductivity, Pulse oxy-meter needed to be worn at ear or at finger. Electrocardiography can lead to skin irritation if used for long term monitoring or used for heart monitoring of old age person. ECG could also causing Skin damage of newborn babies, which is very sensitive to any chemical solution. Importance of HRV and need of unobtrusive measurement of heart related parameters inspired us to develop an unobtrusive and non-invasive method which at the same time require less setup and technician unlike ECG and also easily accessible. We developed method for unobtrusive and non-invasive measurement of pulse rate and HRV. We tested our method for variation in skin color, sex, and different user's states. To record variation due to irritation sate we compelled our subjects to wear napkin. To record variation after physical activity we took video of subject after 100 meter running. Obtained results suggest that human behavior, mental state is affecting HRV. With this analysis of our results we concluded that it is possible to use HRV parameter for various HCI applications.

**3. Methodology :**

Implemented algorithm includes modules for detecting face in video frame, tracking feature points on face in every frame, Trajectory filtering and component analysis to represent frames on dimension corresponding to pulse. Complete detail of modules are as follows:

**3.1 Face Detection** *[148]***:**

I am extracting information from vibration of human head, that's why true detection of face is very important for further processing. There are various face detection algorithms available in literature, but Viola Jones face detection algorithm is Robust and real time implementable. This face detection algorithm provides a face detection framework which is very fast (Real time Processing) with Good detection rate (99%-100%) and very low false negative rate. This framework is contributed by three main components.

*1. Integral Image Representation and Feature calculation*: Integral Image representation of an image reduces number of array references and arithmetic operators to calculate area under rectangle or square. Value at location

(x, y) in Integral Image matrix is calculated using given equation (1).

(1)

Where:

N is new Intermediate Integral Image Representation

*O* is original Image

Pixel (x , y) of new Integral Image is calculated by adding all pixel values above and to the left, including value at current pixel (x , y) of original image (as shown in figure 3.1(d)). Following algorithm calculates values of Integral Image at any location (x , y).

*Algorithm for Integral Image Calculation:*

for (x = 1 ; x <= image\_width ; x++)

for(y = 1 ; y <= image\_height ; y++)

if (x < y)

*N*(x , y) = *N*(x , y - 1);

for ( i = 1 ; i <= x ; i ++)

*N*(x , y) = *N*(x , y) + *O*(i , y);

end

else

*N*(x , y) = *N*(x - 1 , y);

for ( i = 1 ; i <= y ; i ++)

*N*(x , y) = *N*(x , y) + *O*(x , i);

end

end

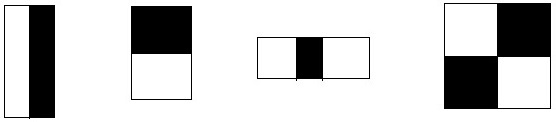
end

As shown in figure 3.1(e) for calculating area under rectangle I need only four array references and three addition and subtraction operators. Point 1 is sum of sum of values under rectangle A, point 2 is sum of A + B, point 3 is A + C and point 4 is sum of A + B + C + D. Area of rectangle D is 4 + 1 - 2 - 3 i.e. (A + B + C + D) + A - (A + B) - (A + C). Integral image representation made calculation efficient with only 4 array references and 6 array references for calculating rectangular sum and for calculating the difference between two adjacent rectangles respectively with the reduced number of addition and subtraction operations.

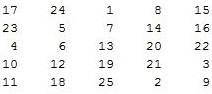
Simple 2 rectangle , 3 rectangle and 4 rectangle features are calculated. These rectangle features are Primitive features compared to features which can be calculated after applying steerable filters. Steerable filters like edge filters, corner filters provides details about edges, corners, boundaries etc, which are of little concern for the case of face detection as suggested by Paul and Michael. Rectangle features (i.e. Haar like operators) capture structural property of face (Shown in figure 3.1(b)) as compared to steerable filters which capture appearance or texture details in the form of edges, corners, contours etc. To capture distinct structure at every scale image pyramid concept is implemented by Paul and Michael. Size of the image in next higher level is 1.25 times smaller than the size of previous lower level. Paul and Michael used bilinear interpolation to implement the pyramid. Paul and Michael derived set of 1,60,000 rectangle features for 24x24 from 4 primitive rectangle features with variation in size and scale to capture every aspect of face structure.

a

b

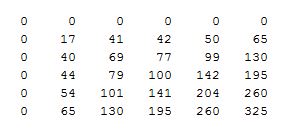


c



Original Image

d



Integral Image

e

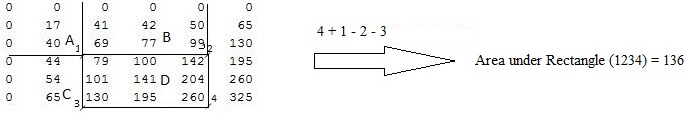


Figure 3.1. (a) Rectangles showing "Haar" like features. (b) Haar features applied on face (c) Original Image (d) Integral Image Representation (e) Area calculation under rectangle using Integral Image

*Learning Strong Classifier Out of Weak Classifiers (Ada-Boost):* Each Feature in feature set supplied from previous module are used as weak classifier for given positive and negative training examples with threshold. Every feature is equivalent to decision tree stump and working as a weak classifier with optimal threshold value. They are weak classifiers because even strongest classifier hardly can give accuracy more than 51%. Best feature has relatively greater accuracy and awarded higher weight and other features are awarded by low weights. Most of the low weight features are classifying incorrect classification of previous round as shown in figure 3.2 . Final Classifier is the Linear combination of these weak classifiers with assigned weight. A feature is discarded If it is giving accuracy less than a defined threshold.

Final classifier is:

H(x) = sign (w1h1(x) + w1h1(x) + + wnhn(x))

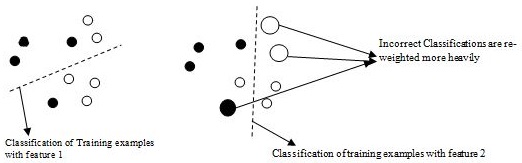


Figure 3.2 Classification using weak classifiers.

*Attentional Cascade:* Third component is attentional cascade which is a method of combining classifiers with trained threshold, weight and no. of classifiers per stage to give high detection rate and low false positive rate, has focus of attention in promising face like areas and lower calculation by discarding background regions of the image. Cascade arrangement of classifiers gives additional advantage of discarding most of the background region in first stage itself, so subsequent stages require less calculation. Each stage of cascade has committee of features as shown in figure 3.3.

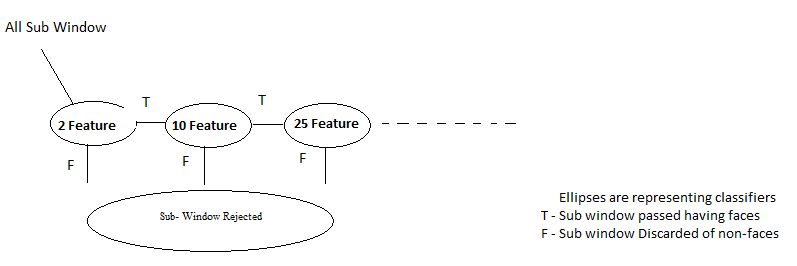


Figure 3.3 Cascade of Classifiers Grouping Features

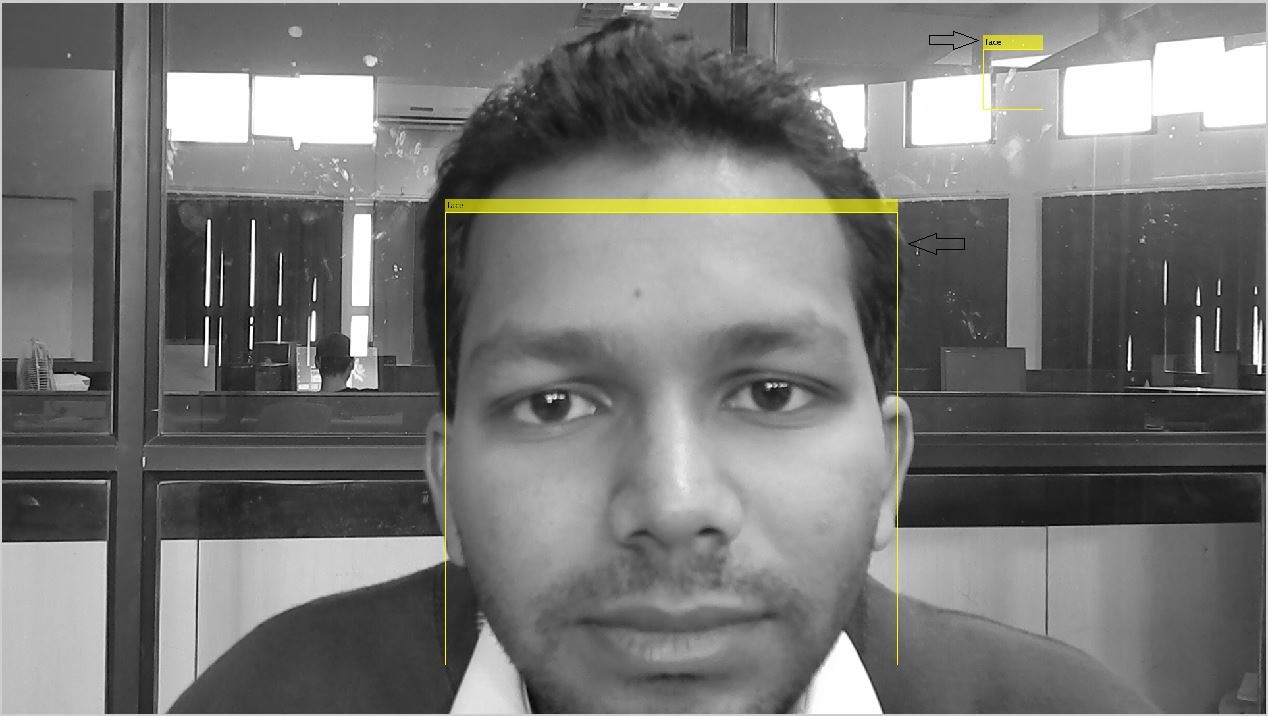
I used matlab inbuilt function "CascadeObjectDetector" in vision toolbox with following values of parameters as required by my application.

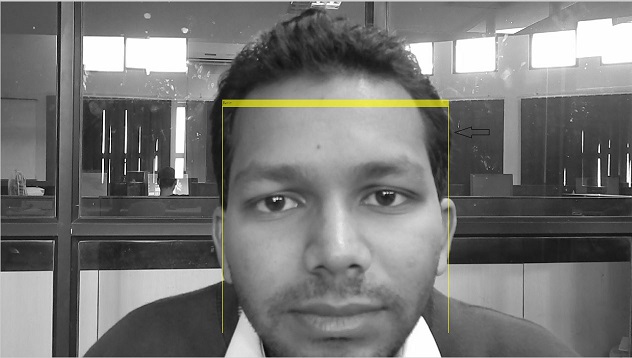
Classification Model: I used Fontal Face as a classification model because I restricted my subject to sit idle with upright and forward facing. Minimum Size: This parameter defines size of smallest detectable object. I captured video for my application where most of the space in frame is covered by subject's face. So size of sub - window framing face only is large. That's why I selected large Minimum Size of detectable target. It also removes chance of false positive in case of cluttered background.

Maximum Size: This parameter sets upper limit on size of detectable target. I passed height of image for upper limit.

Threshold Merge: This parameter is very important to decrease false positive rate. Sub - windows are passed to the classifier and these sub-windows are adjacent to each other that's why multiple detections occur on the same site. To short out detection windows which are detecting false objects, we tuned this parameter. Group of collocated Windows that meet this threshold are combined to get one window around the face and others groups are discarded. False positive rate can be reduced by increment in this threshold value. Threshold value ensures that object is detected multiple times.

After Tuning parameters I succeeded in discarding False detection for all subject's videos as shown in figure 3.4.





After Tuning I discarded one false negative

Figure 3.4. Output of Face Detection Algorithm.

**3.2 Region Selection:**

Face region detected by face detector includes whole face, but Our region of interest is some part of face that's why bounding box returned by face detection method needs to be adjusted to include required part of face only and exclude others. This Module requires user interaction to select height and width of region for feature extraction. User will reposition a bounding box returned by face detector to set a region for feature calculation. It is not enough because we have one more problem of excluding eye region from selected area because eye blinking for my application is noise. Eye blink has no relation with heart rhythm. Features taken in this region will cause additional movement due to blink and retina movement. Another problem is with tracking. Movement caused by eye blinking is large and traceable with tracker tuned for small movements. Some constants and ratios has been used to find eye region in whole face without using any eye detector. Using detector can cause computational overhead whereas a code snippet which I used requires only 3 additions and subtractions and 4 multiplications. Resultant eye region specification will be same as bounding box (upper left corner coordinates, width and height) as shown in figure 3.5.

a





c



b



Figure

Figure 3.5. (a) User Interactive window to select height and width factor (b) Required face region (c) Rejected Eye region

**3.3 Feature Extraction:**Features are distinctive attributes which provide useful information. Handful of unique features can represent whole scenario. Good feature selection is very important to acquire useful information. Feature are selected from first frame and in subsequent frames these features are tracked using optical-flow point tracker. Features for tracking should be easy to track and should not lead to "aperture problem". Corners are very good features for tracking, but texture under ROI which we are using for feature extraction don't give too many corners. There is also problem of skin tone and fairness which vary from person to person, so in some cases it is very rare to get a point where two edges meet. That's why we are using edges as our features and detecting these edges by "Canny Edge Detector" in region of interest. These set of edge points defines my feature set for normal and running case. For the case in which subject is wearing mask corner detector can be used. We used "Harris Corner Detector" to detect corners in frame. These corners serving the purpose of feature for the subject wearing mask.

**3.3.1 Corners:** Corners are unique points which resolves aperture problem (All points on edge looks same). Corners are points with large derivative in all directions except in directions of lines which are making corners[149]. I used Shi and Tomashi corner Detector. We can see pixel values around corner are far greater than value at corner i.e there is large variation in pixel values consequently greater Eigen values in all directions except in the direction of line as shown in figure 3.6(b).

b



a

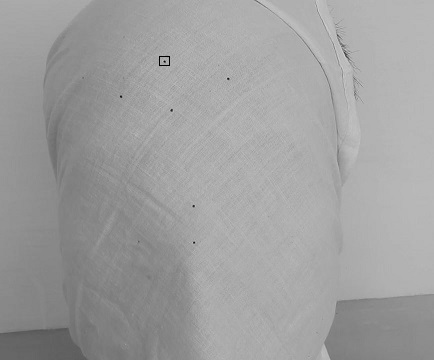


Figure 3.6. a.) Face with mask being marked b.) Corner and values around corner

**3.3.2 Canny Edge Detector:**Although Canny edge detector algorithm is complex, but performance in terms of true Edge detection is superior than other edge detection algorithms. It underlies on three principles [150]:

1.) Good True Positive Rate 2.)True Localization 3.)Reduced number of Local Maxima around true edge point

Steps to calculate canny edge detector [150]:

1. Image Smoothing using Gaussian Window Kernel.

2. Calculation of Gradient Magnitude Image and Angle Image .

3. Non-maximum Suppression on Gradient Magnitude Image to get True Edge Points.

4. Apply lower threshold, upper threshold on image obtained after non-maximum suppression and analyze connectivity to detect and link edges.

a b

c d

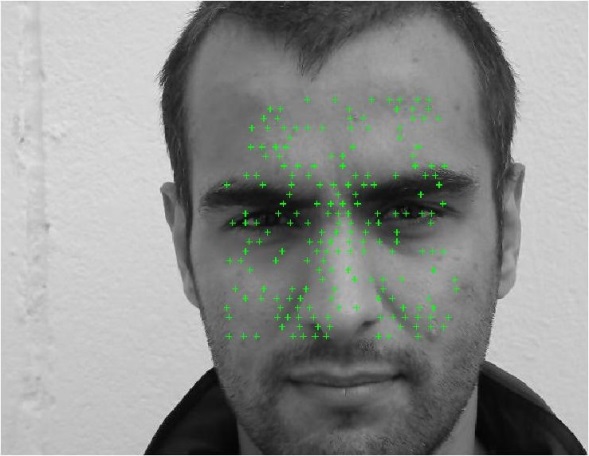
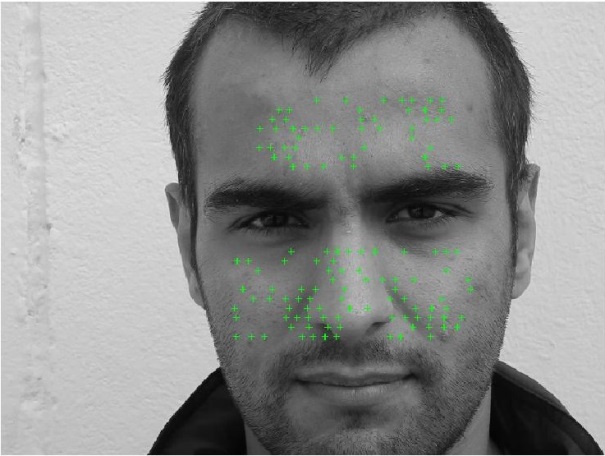
 

Figure 3.7. a.) Image before canny edge detector (b) Image after applying canny edge detector (c) Feature points corresponding to edge points locations (d) Features after removing eye region

Figure 3.7 is showing snapshot of features obtained after applying "Canny Edge Detector".

**3.4 Tracking:**

Features calculated from previous module are fed to this module to get trajectory of these features. Features points are changing position from one frame to other frame due to head vibration. We are tracking these feature points using Lucas - Kanade point tracker algorithm. This algorithm rests on three principal assumptions [146]:

1. *Brightness Constancy:* A pixel from the image of an object in the scene does not change in appearance as it (possibly) moves from frame to frame [146].

Equation for same concept is: I(**x** , t + 1) = I(**x** + **d** , t)   
Where :

**x =** co-ordinates in image

**d =** Motion Vector (Real values i.e. Sub-pixel Accuracy)

2. *Temporal Persistence or Small Movements:*The image motion of a surface patch changes slowly in time. In practice, this means the temporal increments are fast enough relative to the scale of motion in the image that the object does not move much from frame to frame [146].

3.*Spatial Coherence:*Neighboring points in a scene belong to the same surface, have similar motion, and project to nearby points on the image plane[146].

Optical flow equation shown in equation 1 being calculated to get flow vector (u, v)at each feature point by getting optimal solution for matrix shown in equation 2. We are adding u and v with previous location co-ordinates x and y respectively to get new locations co-ordinates x' and y'. Head movement due to pulse arrival is periodic because heart contraction and relaxation is a cyclic event. It is like pendulum is moving in two directions. That's why tracking is performed by calculating point correspondence between first frame and all other frames 2,3,4.........m in video. Parameters like height of Pyramid, Error threshold and block size are selected to capture small movements and global flow i.e. flow due to head movement rather than flow due to local patch variation. Muscle movements and sudden change in light patterns can corrupt signal. So we are processing tracking results to recognize these movements. Due to blood flow head moves in upward and downward direction i.e. in y direction that's why we are recording only y co-ordinate. Recorded trajectories of feature points are not in same scale. So I am calculating zero mean trajectory and normalizing amplitude between -5 to 5. We are recognizing those points which are deviating from flow pattern and eliminating these feature points.

Optical Flow Equation: fxu + fyv = -ft (1)

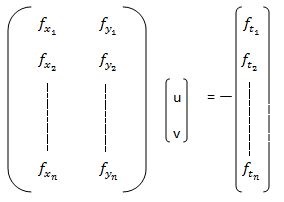
fx = Spatial derivative of image with respect to x axis. (Known)

fy = Spatial derivative of image with respect to y axis. (Known)

ft = Temporal derivative with respect to time. (Known)

u and v are optical flow vectors. (Unknown)

Values in the following matrix are derivatives of neighborhood pixels which are incorporating in optical flow calculation for one feature point. For every feature point Optimal solution for matrix containing respective neighborhood pixel derivatives for each feature point is calculated. This calculation is iterative in every pyramid level until error threshold is reached. Optical Flow values obtained in higher level of pyramid are passed to lower level of pyramid to facilitate initial guess for lower level till original dimension encountered. Finally obtained optical flow vector with original dimension is added to previous location of feature point to get new locations.



(2)

New Co-ordinates: x' = x + u and y' = y + v

Accuracy and Robustness are two parameters to measure performance of any tracking algorithm. In fact there is trade-off between these two parameters. How much localized calculation is done to find velocity vector defines accuracy and it relates to sub-pixel. More localized calculation leads to less chance of error in velocity calculation where two patches are moving with different velocity due to different texture pattern[146]. And robustness is good if tracker can track point even in light changing condition and large motion. Tracking of large motion requires large window size which leads to less accuracy. This Problem can be solved by using the concept of Pyramid as Shown in figure 3.8.



(a)

ImageL

ImageL - 1

Down-Sampling by 2

Gaussian Low Pass Filter (Ant aliasing)

(b)

Fig 3.8 (a) Visual Representation of Pyramid (b) Schematic Diagram of Pyramid Construction

Figure 3.8(a) depicting visual representation of pyramid construction. A black line annotated at every level of pyramid has increased length by more than double at very next lower level (Original Image is at level 1) because level L-1 is double in resolution than level L. Every level will pass optimum value of translation vector (dx, dy) by refining it until error residual is optimized.

Figure 3.9 is showing snapshot of trajectory which I got after tracking feature points.

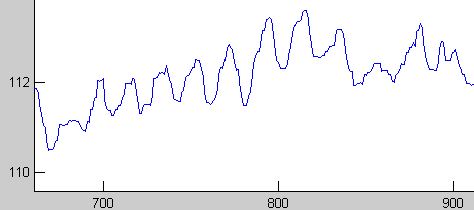


Figure 3.9 Trajectory of a Feature Point Tracked with Lucas - Kanade Tracker

3.5 Cubic Spline:

Sudden change in amplitude of the signal due to pulse arrival is sum of high frequency components. We are capturing 30 frames per second i.e. 30 samples per second. According to Nyquist criteria I can recover maximum 15Hz component. Which is not enough to get sharp peaks. That's why I am up sampling my signal by 5 samples using Cubic Spline interpolation to capture sharp peaks. Normally ECG records signals at 250Hz to recover sudden electric impulse due to ventricular depolarization. This impulse is so quick, but movement in head due to pulse arrival is not this much quick. So we are increasing sampling frequency of signal from 30Hz to 150Hz using cubic Spline interpolation.

Interpolation is the process of interpolating values of for the given data of (n+1) points using n or less degree polynomial. Runges's phenomenon is a problem with higher degree polynomial Interpolation which produces vibrations at the edge between interpolation points called "Numerical stability" as shown in figure 3.10. As we are going higher in degree error is increasing for points between interpolating points and oscillations are increasing.

This oscillation problem is addressed by Schoenberg in 1946 and he given the method of Splines. Literal meaning of Spline is "a thin strip" which can be bent easily which is imitation of draftsman's Spline as shown in figure 3.11. Spline interpolation is a "Piecewise Interpolation" using lower degree polynomials instead of using one higher degree polynomial. Putting together all these lower degree polynomials will result Spline. Spline interpolation follows interpolation condition that curve should pass through all interpolation points with zero error i.e. if g(x) is spline and (x0,f(x0)), (x1,f(x1)), (x2,f(x2)),.........(xn,f(xn)) is given data then following condition should be followed [147]:

g(x0) = f(x0) = f0 g(x1) = f(x1) = f1 . . . . . . g(xn) = f(xn) = fn

Here g(x) is made of n-1 cubic polynomials namely q0(x), q1(x), q2(x) . . . . . . . . qn-1(x)

Another advantage of Piecewise approximation is localized approximation i.e. approximation on a point, depends on interpolation points near to evaluating point, so change in particular interval points only affects points approximated by polynomial calculated based on this interval.

Cubic Spline interpolates given data using "Piecewise Cubic polynomials" to create a smooth arc, subject to condition that it should go through given number of points with zero error and should have continuous first and second order derivative [147]. i.e.

qt'(xi) = qt+1'(xi) and qt''(xi) = qt+1''(xi)

Equation kj-1 + 4 kj + kj+1 = (fj+1 - fj-1) itself confirms continuity in second order derivative

function Spline:

For ( I = 0 ; I < n ; I++) {

I = Input no. of intermediate points

calculate coefficients Ci0 , Ci1 , Ci2 , Ci3 with following equations

Ci0 = fi

Ci1 = ki

Ci2 =

Ci3 =

qj(x) = Ci0 + Ci1(x - xi) + Ci2(x - xi) ^2 + Ci3 (x - xi) ^3

For ( j = 0 ; j < I; j++) {

Find intermediate points using qi( xj)

}}

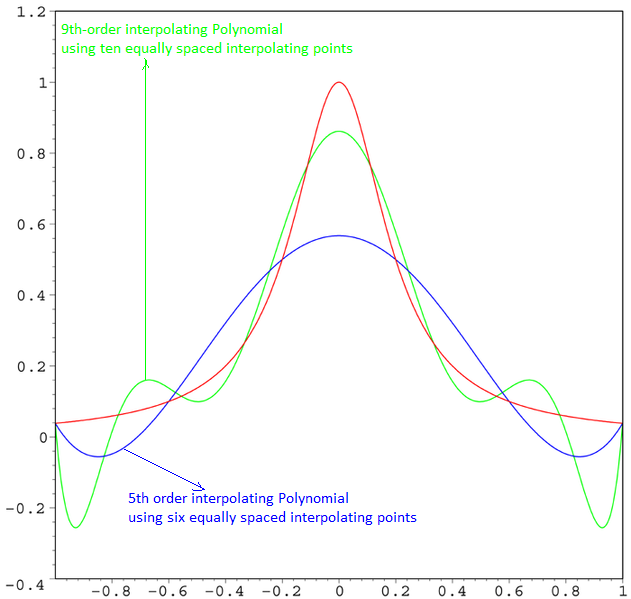
****

Figure 3.10 Runges's phenomenon

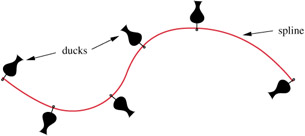
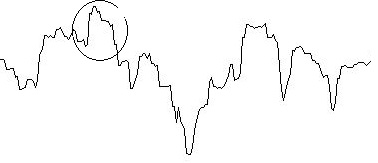
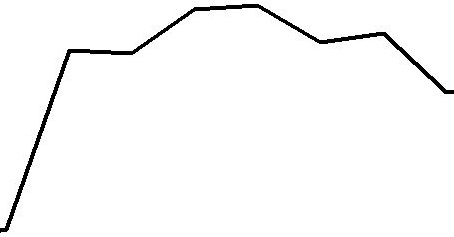
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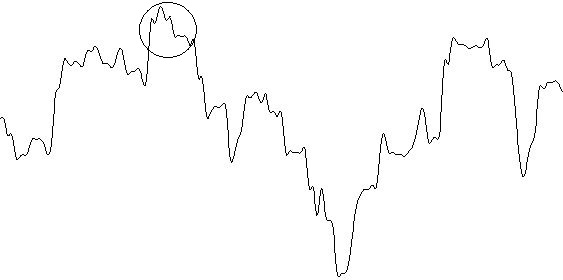
Figure 3.11. draftsman's Spline





a

b



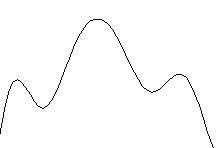


Figure 3.12. a.) Trajectory Before Cubic Spline b.) Trajectory after applying Cubic Spline

Figure 3.12 is showing snapshot of obtained smoothness in the signal after applying cubic spline.

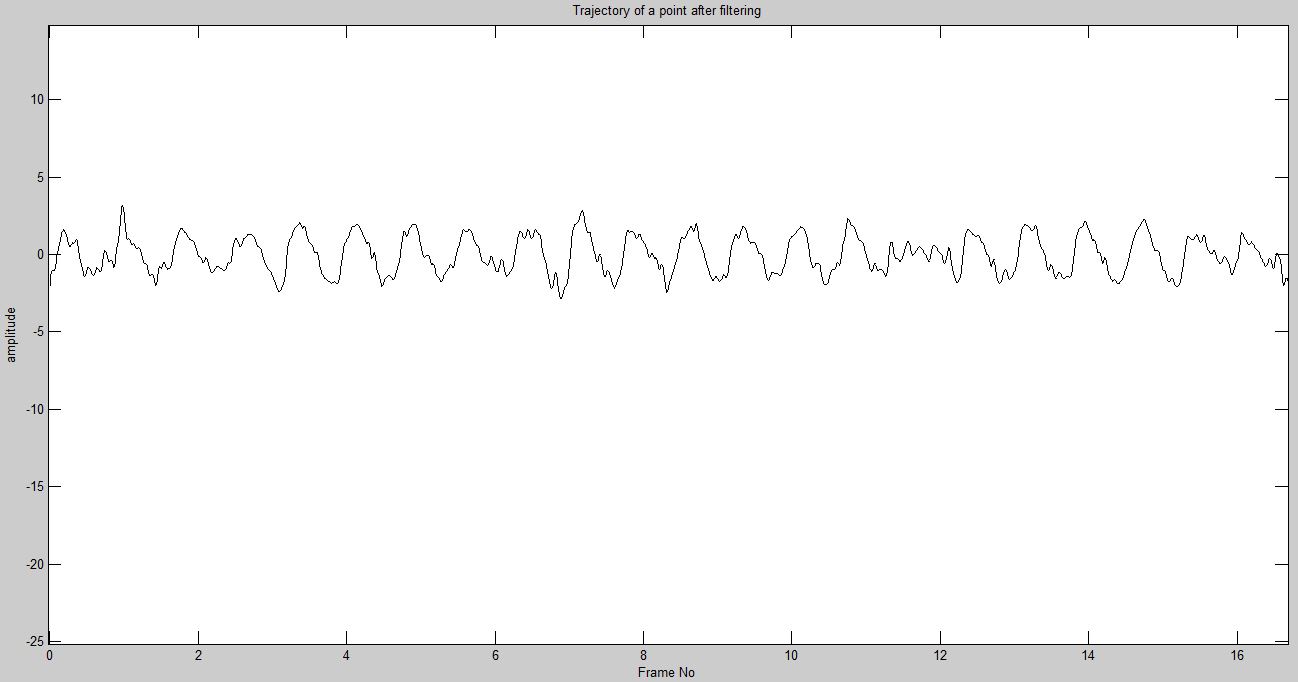
3.6. Filtering:

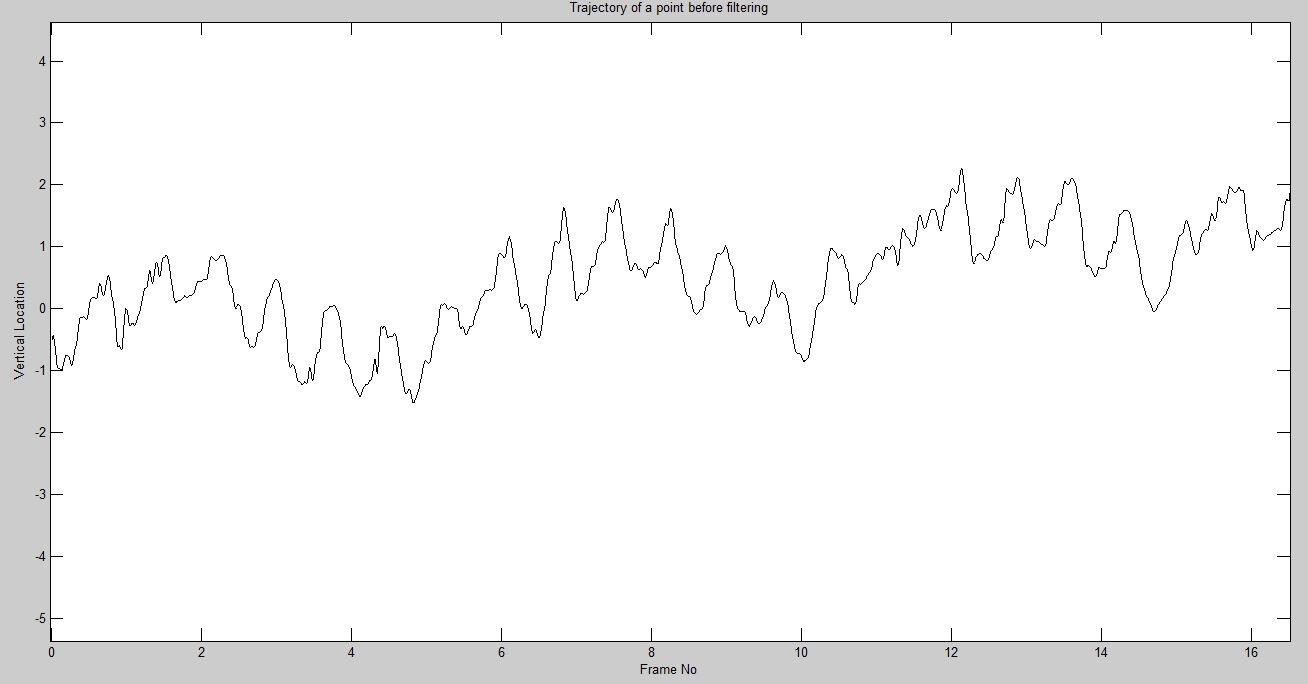
Trajectories which I am getting do not have variations due to arteries pulsation only. Movement due to respiration causing base line drift and present throughout the trajectory. Other than respiration head vibrations interfere signal randomly. Head vibrates due to structure of head neck joint. The head-neck joint has “vertibre” positioned over each other and connected with two joints called Facet Joints. The cervical disks in head neck joint are spring like system which is fixed at both the ends.. Due to downward movement of head facet joints stretched and discs are being squeezed in forward direction. A reaction force is generated by these discs to get equilibrium state, causing squeezing in other discs in any direction. Due to “Stack structure” and “spring like system”, this whole system vibrates causing vibration in head which introduce noise in the signal. Local muscle movement is another source of noise in the signal. We are using Butterworth high pass filter with cut-off frequency is 0.75Hz. Cut-off frequency is selected such that along with other noise, base line drift should be filtered, with no loss of desired information. We are using butter-worth filter because it gives maximally flat Pass-band" with controlled transition period tuned by its order. Due to maximally flat pass-band it allows no ripple in pass-band consequently no vibration in gain for pass-band. As we go high in order transition period reduces. But there exists trade-off between stability and transition period that's why we are using 5th order "butter-worth high pass filter". Since we have to recover peaks due to pulse arrival that's why instead of Band-pass filter, we are using High-pass filter.

b

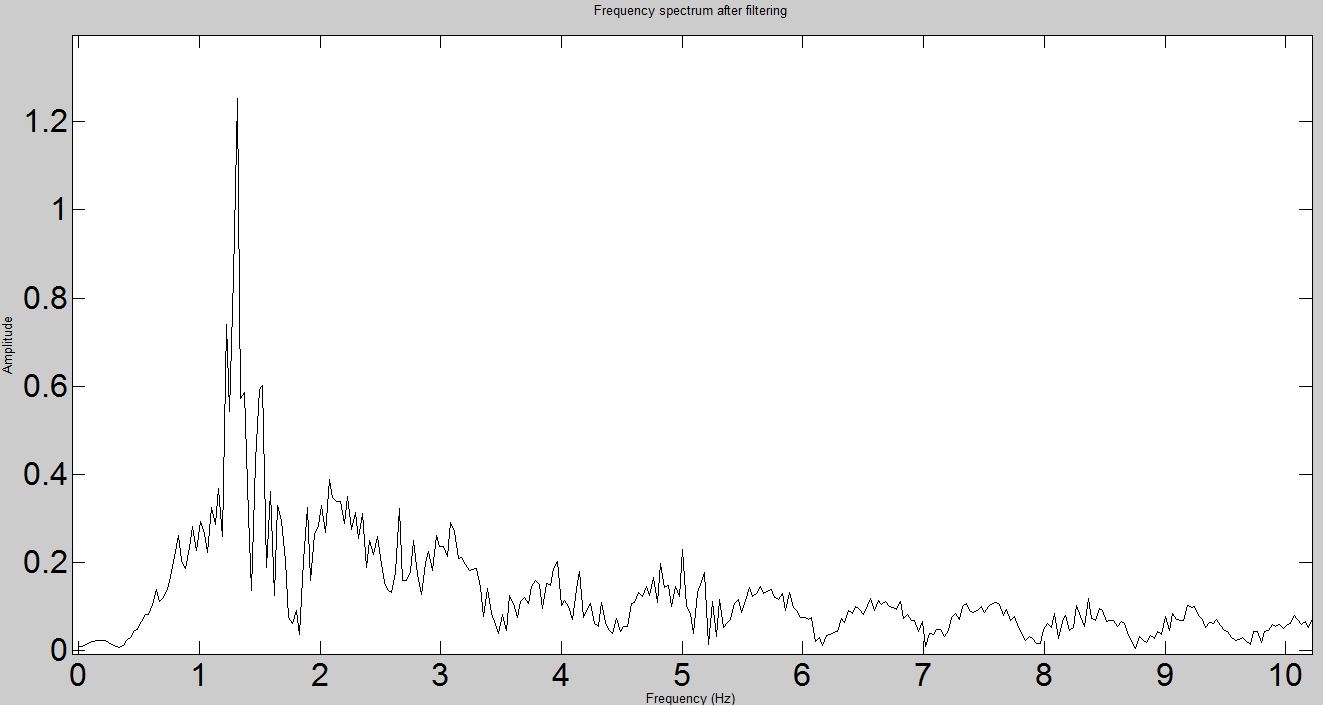
a

Figure





d



c

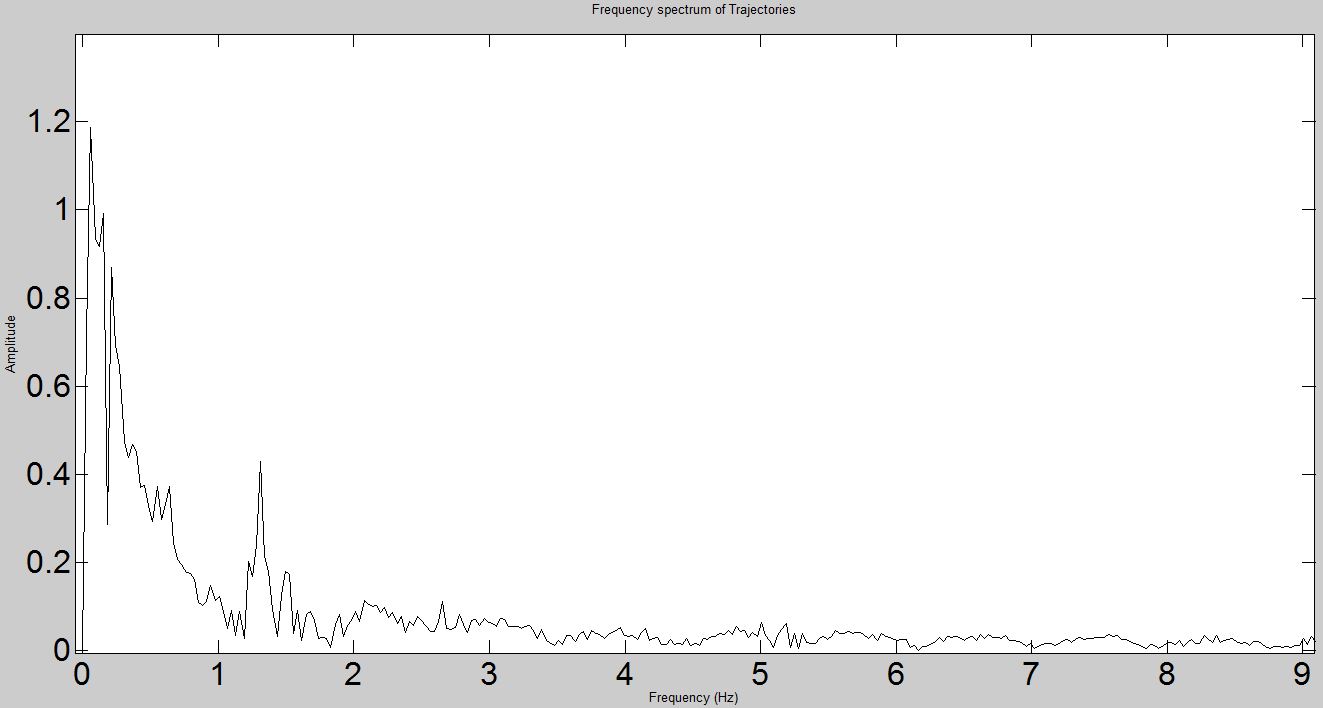


Figure 3.13 (a)Trajectory of feature Point (b) Trajectory of feature point after filtering

(c) Frequency Spectrum of Trajectory (d) Frequency Spectrum of Trajectory after filtering

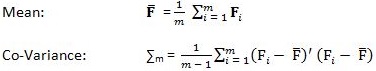
It is clear from figure 3.13 (c) and (d) that Filtering removes interference due to respiration.

Table 3.1 Standard values of Respiration Rate and Heart Rate and adapted cut-off frequency

|  |  |  |  |
| --- | --- | --- | --- |
| **Category** | **Respiration Rate (Breaths/ min.)** | **Heart Rate (Beats/min.)** | **Cut-off Frequency for High Pass filter** |
| Newborn 0 - 6 weeks old | 30 - 60 | 70 - 190 | 0.83 Hz |
| Infants 1 - 11 months old | 25 - 40 | 80 - 160 |
| Children 1 - 4 years old | 20 - 30 | 80 - 130 |
| Children 5 - 6 years old | 18 - 25 | 75 - 115 | 0.75 Hz |
| Children 7 - 9 years old | 12 - 15 | 70 - 110 |
| Children 10 years and adults | 12 - 20 | 60 - 100 |
| Well Trained Athlete | 10 - 15 | 40 - 60 | 0.58 Hz |
| After Running |  |  | Should be taken at small interval |

**3.7 Component Analyzer:**

We observed that even after above processing like filtering, point elimination, still we left with corrupted signals. This signal is corrupted due to three reasons. First reason is random variation in signal due to head vibration subjected to head neck connection by stack of cervical disks, second reason is variation due to involuntarily muscle movements and third reason is variation in local surface texture, consequently variation in optical flow pattern. Position of feature points are varying not only because of blood flow but because of respiration and above three movements also. Respiration frequencies are filtered out by filter. Here we are Using PCA to getting signal which is maximally varying due to pulse component. Since signal has various elementary movements along with pulse movement and these elementary motions are components of original signal, using "Principal Component Analysis" we are getting principle components of variations. Formally we have n feature points f1......fn representing n dimensional position of head and m frames O1.......Om. At a particular time t frame Ot is represented by a column vector of features [f1(t),f2(t),f3(t),..........,fn(t)]t. We need to calculate mean and covariance of m x n dimension matrix using following formula:



Eigen vectors of Co-Variance matrix are Principal axes of variation and linear combination of feature points. Eigen vector corresponding to maximum Eigen value represents axis of maximum variation. PCA returns matrix фn (n x n) of n non-zero Eigen vectors ф1, ф2, ф3,........фn and Ѱn Diagonal matrix of Eigen values λ1, λ2, λ3, λ4,............, λn. These two are Inner Product of each 1 x n dimensional frame with 1x n dimensional Eigen vector is giving a signal, varying because of one elementary motion component. Likewise we are calculating signal corresponding to all principal components. Before passing signals to PCA we are processing these signals to find outlier frame. Outlier frames are causing deviation in regular pattern and sudden increase in amplitude because of superficial muscular movements, posture adjustment. We are calculating median of vector length corresponding to each frame. We are

reducing vector length of vectors greater than this median value by 0.75.

a

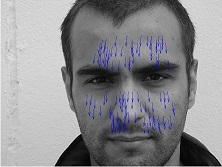
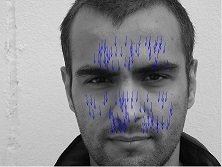
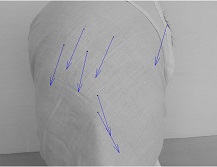


Figure aaaaaaaa

b



d



c

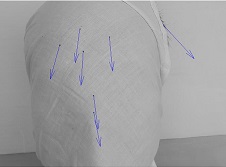


Figure 3.14 a and b are showing two principal components with no mask on face. c and d are showing two principal components where subject is wearing mask.

These Eigen vectors are representing signals corresponding to different - different source of movements. One of the Eigen vectors is representing maximum variation in signal due to pulse. We are calculating power spectrum of projected signal on these components. Signal with new dimension for variation whose total power is maximally contributed by frequency within the decided bandwidth is recognized as desired signal. And this frequency is determined as pulse frequency. Component which is corresponding to pulse frequency is depicted in figure 3.14 where images belongs to videos of same person taken after some interval and with and without mask. It can be observed clearly that co-ordinates of pulse component are varying. We inferred from this observation that Heart functionality varies based on the subject's state and context (Like with and without mask) .

**3.8 Beat Detection:**To detect beat We are using a window. Size of this window is calculated using pulse frequency determined in previous section.

Size of Window = Sampling Frequency / Pulse Frequency

This window we are shifting through signal. A point within the window is qualifying as beat if it is following two criteria. First criteria is if it is greater than at least 10 leading points and 10 following points. Second criteria is its value should be greater than one-fourth of maximum value of signal. Time between beat to beat can vary because of natural variation in heart cycle.

*Summary of Methodology:* Flow Chart shown in figure 3.15 is summarizing whole algorithm.

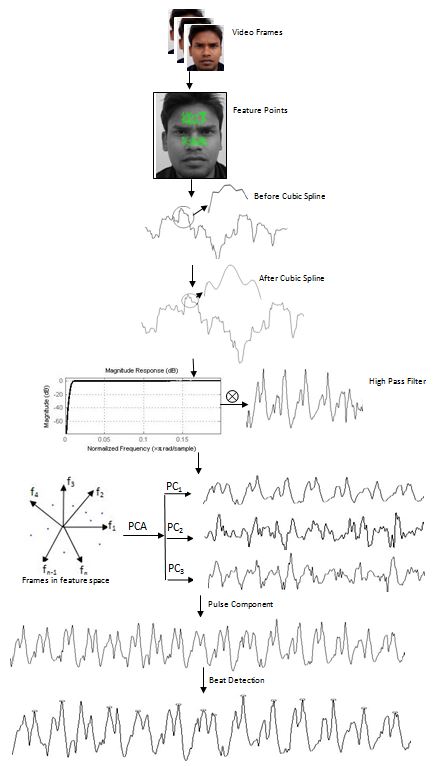


Figure 3.15 Flow Chart of implemented methodology

**4. Experiment:**

I am recording video of subjects where subject is sitting idle near to camera. Area of camera frame is covered by subject's face as much as possible so that good details can be captured. I used Nikon Coolpix L820 with frame rate of 30 frames per second. Resolution of frame is 640x480. I captured video in natural light and uniform light. For ground truth I counted pulse manually to get actual average pulse rate. I recorded video for 1 minute.

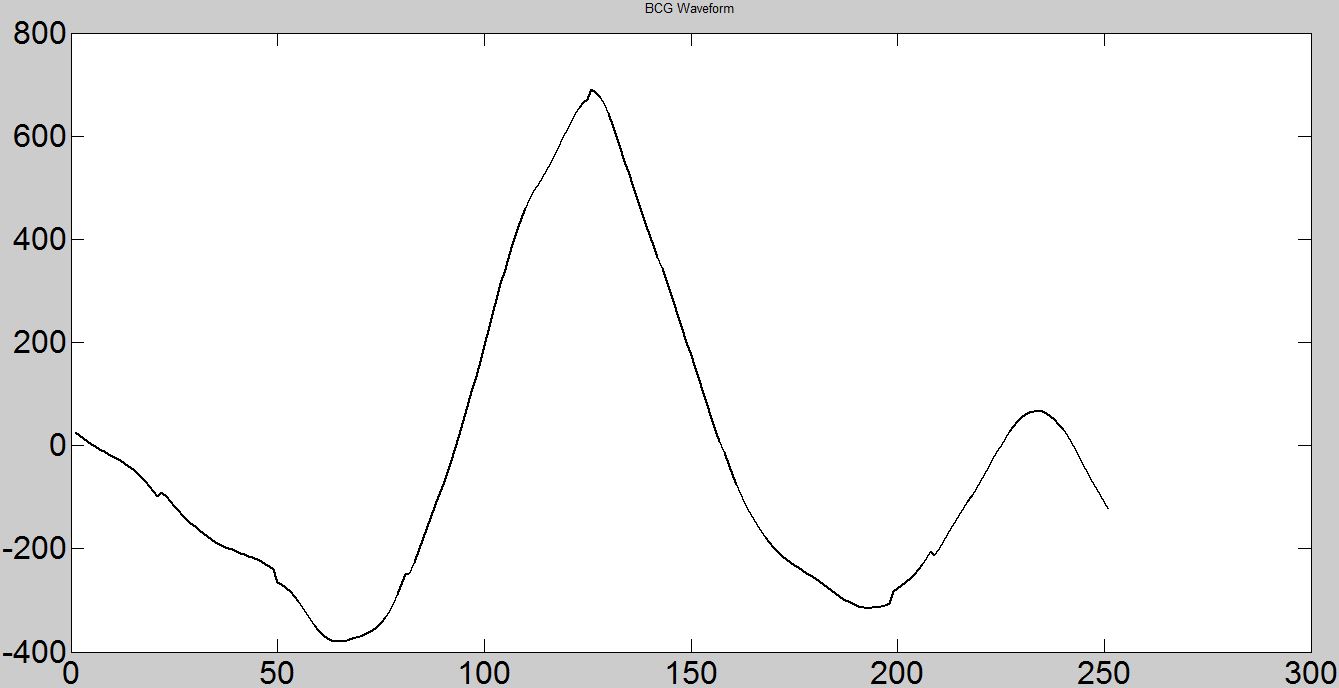
**5. Results and Analysis :**

I tested our algorithm on 11 subjects (10 males and 1 females ) aging between 23 to 28. Dataset has variation in skin color, sex, visuals and physical activity and frame resolution. I am selecting frequency of maximum power from the power spectrum of component corresponding to pulse frequency. This frequency gives information about average pulse rate in one minute. With the beat detection algorithm I detected beat and calculated beat lengths. By compiling results I found that there is maximum no. of counting for bin representing time period which is inverse of average pulse frequency 1.34 for figure 5.2 (a) and (b) respectively. These Histograms belong to same subject in two different states. First histogram is showing beat distribution when subject's face tied up with napkin and second histogram is showing histogram when subject has no napkin on face and in normal state. It can be observed clearly that beat distribution is making cluster around mode. There are variations in beat length .They are because of natural variation in Heart rhythm. But sometimes bins not near to bin which got higher score and corresponding to average beat length, are getting score of 1 or 2 , it could be because of some noise still present in the signal, due to head vibration or involuntary motions. Table 5.1 is showing pulse rate detected manually (actual), using motion and percentage error. I also calculated mode and standard deviation for HRV. Mode is calculated to check which beat length is dominating in HRV graph. I Observed that beat length corresponding to average pulse frequency has more occurrences than other beat lengths. So pulse frequency and beat length distribution is itself satisfying each other. Standard deviation provides information about width of distribution. In order to validate our method I superimposed 20 windows centered at beat location to obtain BCG waveform. BCG wave which I got has similarity with BCG wave described by father of modern BCG Isaac Starr. "IJK" complex can be observed clearly along with other useful nomenclatures as described by Starr. I are getting BCG signal which is showing clear peaks with respect to pulse (Figure 5.3 (a) and (b)). Caption (a) and (b) in figures 5.5, 5.6, 5.7 and 5.8 are four different outputs corresponding to position and state when subject was laid down on bad and when subject came after running respectively. I compared pulse rate calculated with our method and actual pulse rate calculated manually. We are getting mean error only 0.732 % with 14 observations.

Table 5.1 True and observed Values of Output Parameters and error statistic

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Subject ID | State | **Sex** | **Avg. Pulse Rate (Beats/min.)** | | | HRV(seconds) | |
|  | | | **Actual** | **Motion** | **Error** | **Mode(Beat Duration)** | **Standard Deviation** |
| S01(Sudhakar) | Resting | M | 63 | 62.25 | 1.19 | 0.9 | 0.304 |
| S02(Praveen) | Resting | M | 73 | 73.24 | 0.33 | 0.8 | 0.193 |
| Push-ups | 117 | 117 | 0 | 0.54 | 0.235 |
| S03(Pallav) | Resting | M | 70 | 69.58 | 0.6 | 0.8 | 0.226 |
| S04(Prateek) | Resting | M | 76 | 76.90 | 1.18 | 0.8 | 0.333 |
| S05(Abhi) | Resting | M | 75 | 76.91 | 2.55 | 0.8 | 0.154 |
| Running | 113 | 113.52 | 0.46 | 0.4 | 0.292 |
| S05(Tushar) | Resting | M | 84 | 84.22 | 0.26 | 0.7 | 0.156 |
| S07(Manish) | Resting | M | 81 | 80.57 | 0.53 | 0.75 | 0.224 |
| Mask | 81 | 80.57 | 0.53 | 0.8 | 0.089 |
| S08(Dev) | Resting | M | 85 | 84.28 | 0.47 | 0.7 | 0.263 |
| S9(Jigyasa) | Resting | F | 106 | 106.20 | 0.19 | 0.6 | 0.273 |
| S10(Raju) | Mask | M | 108 | 109.8 | 1.66 | 0.56 | 0.092 |
| S11(Prateek) | Lay Down | M | 73 | 73.22 | 0.30 | 0.6 | 0..237 |

b



a

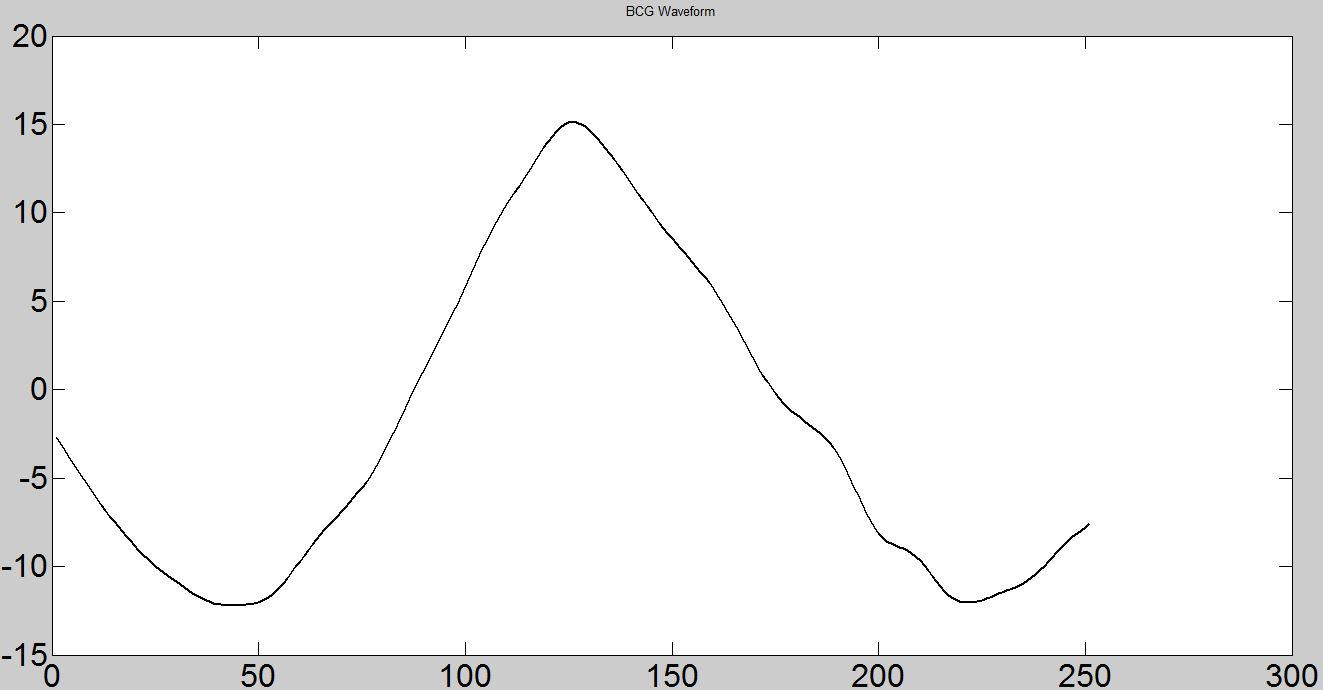
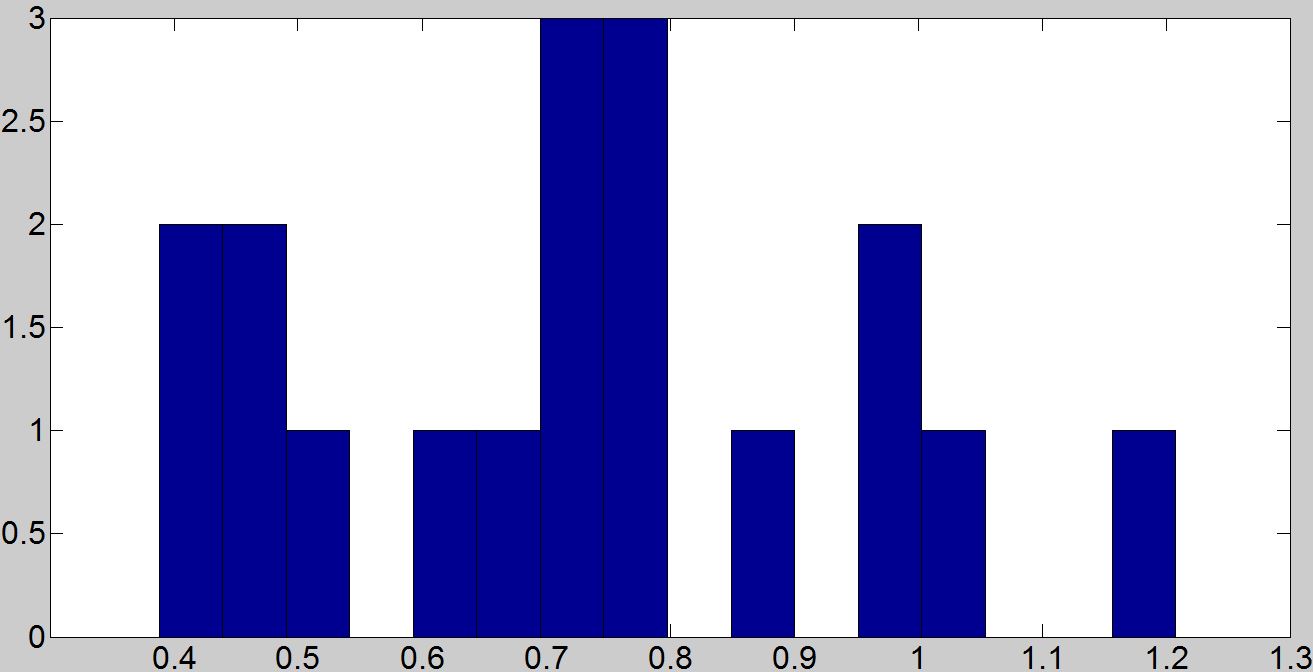


Figure 5.1. Resultant BCG Waveform

b



a

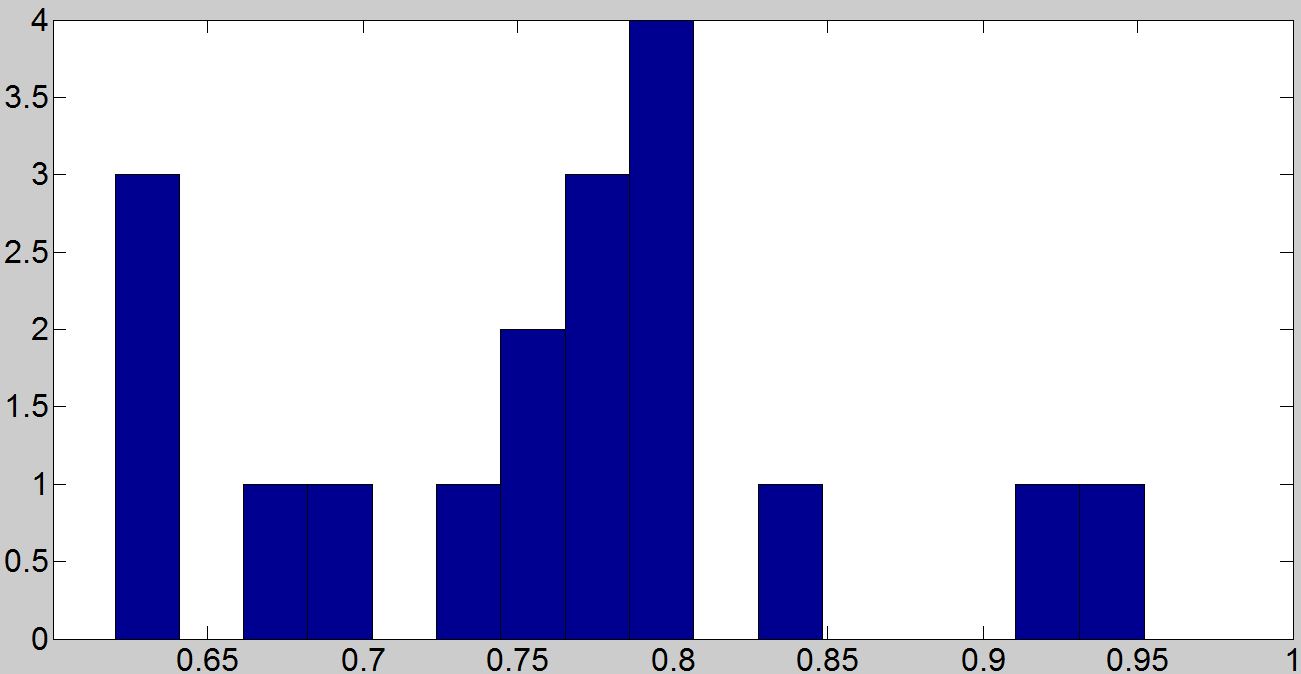
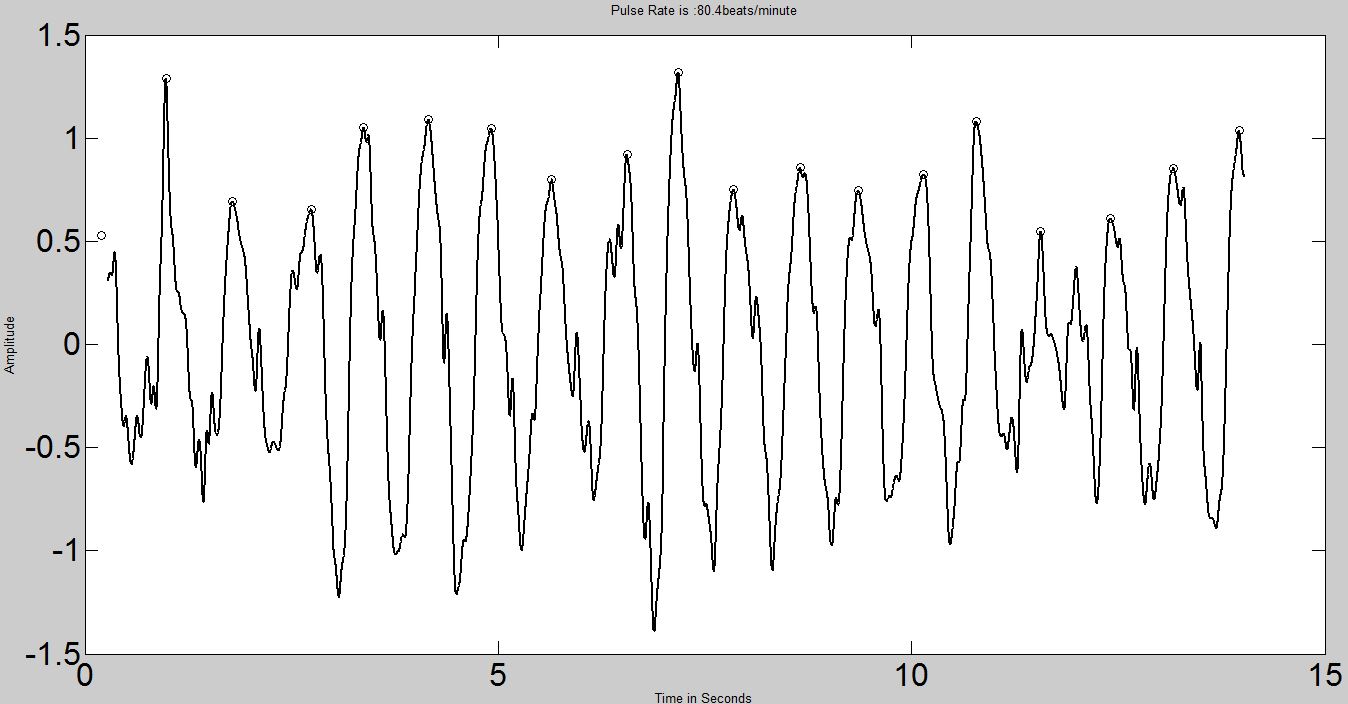


Figure 5.2. Histogram

a



b

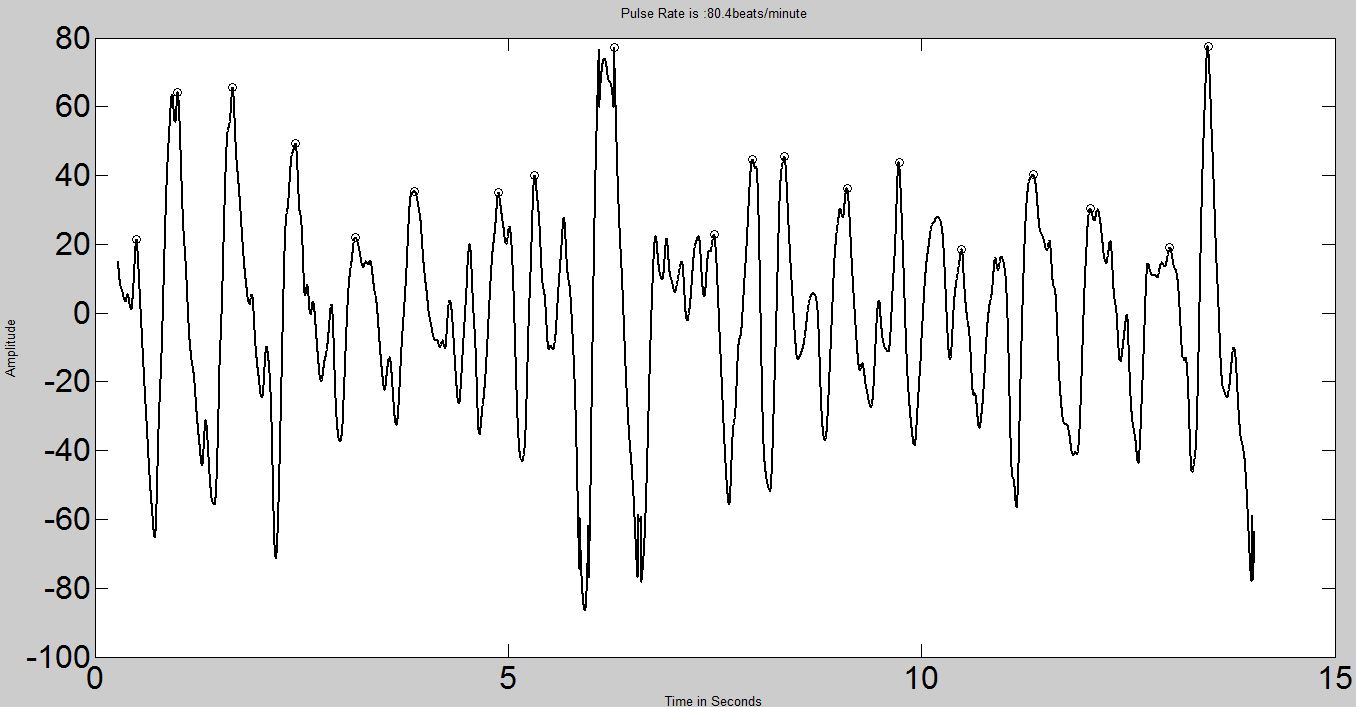


Figure 5.3. Obtained BCG signals



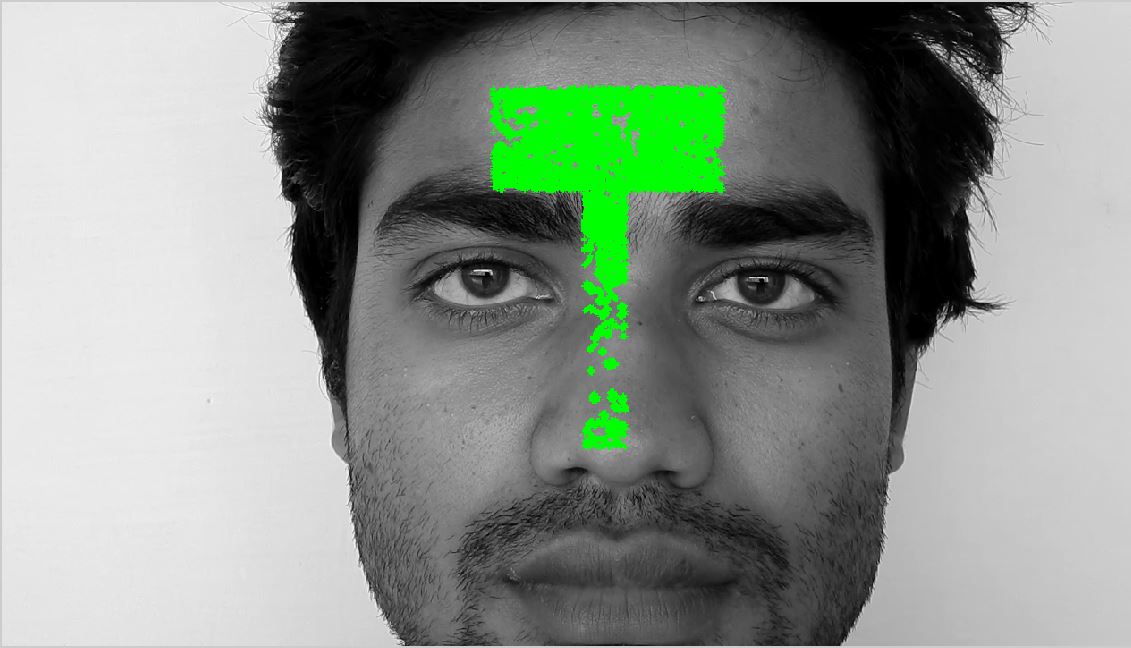
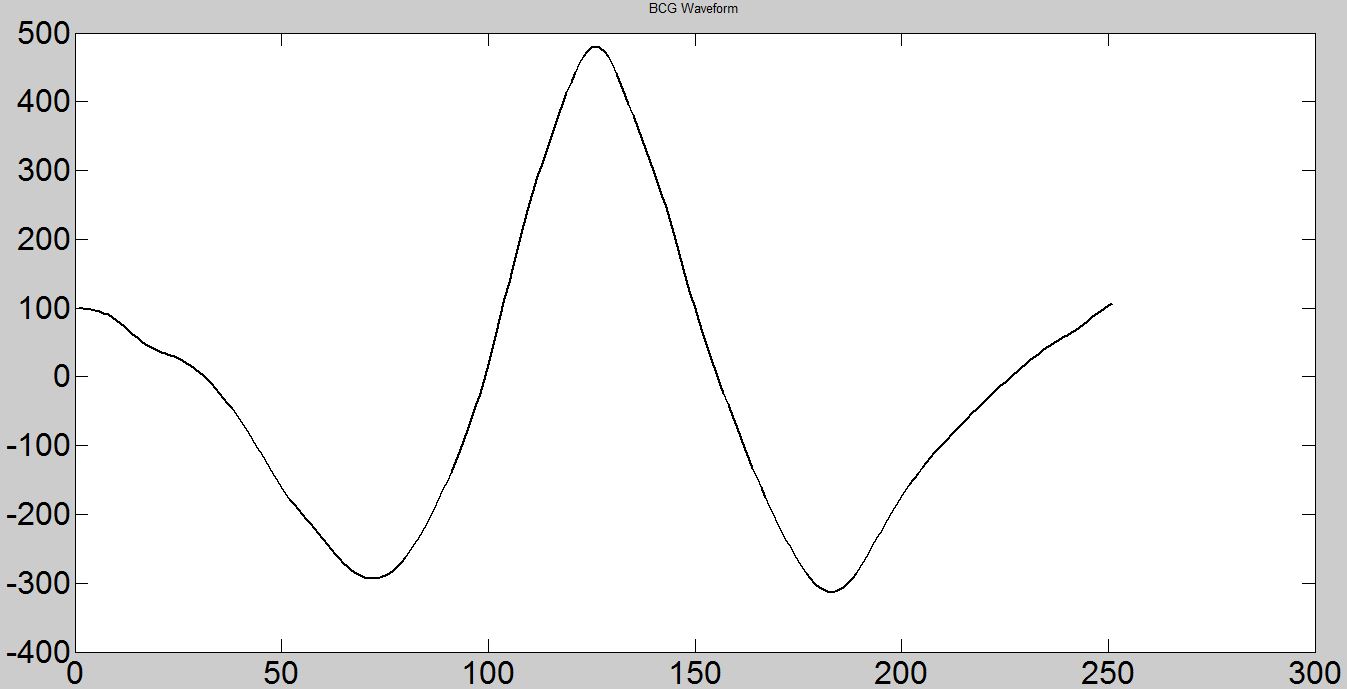


Figure 5.4 Snapshot of Subject

b



a

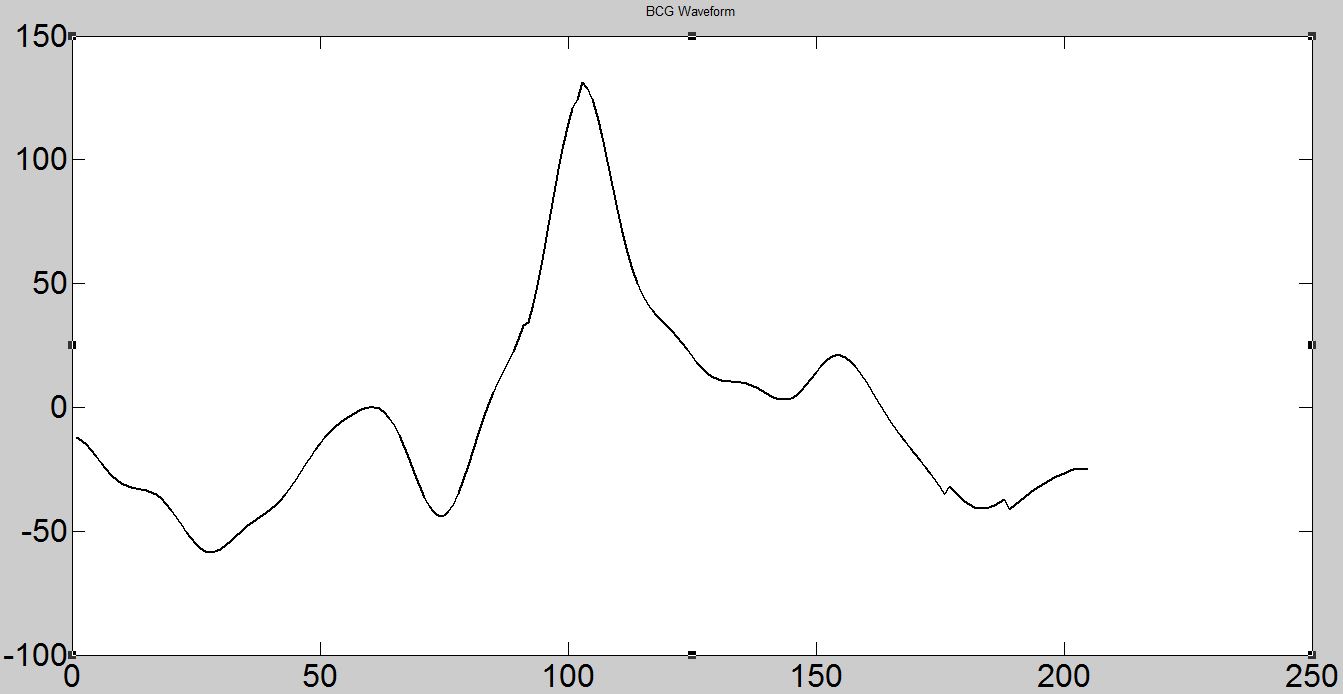
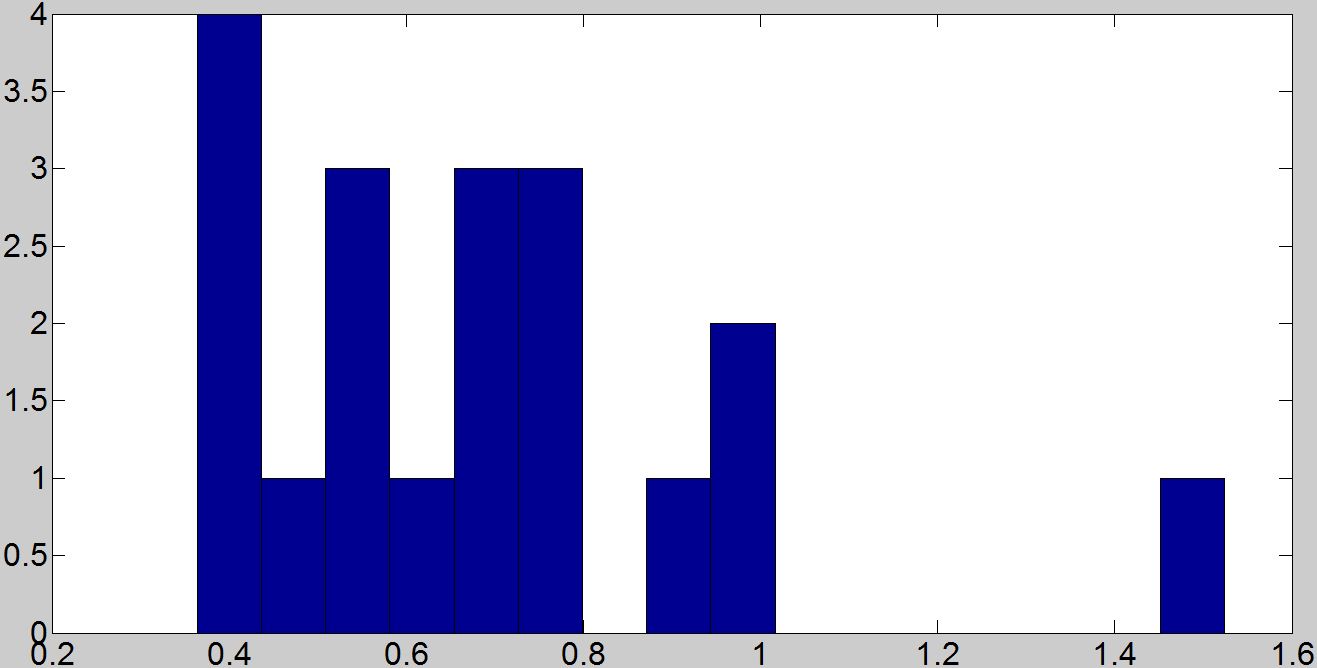


Figure 5.5 BCG Waveform

b



a

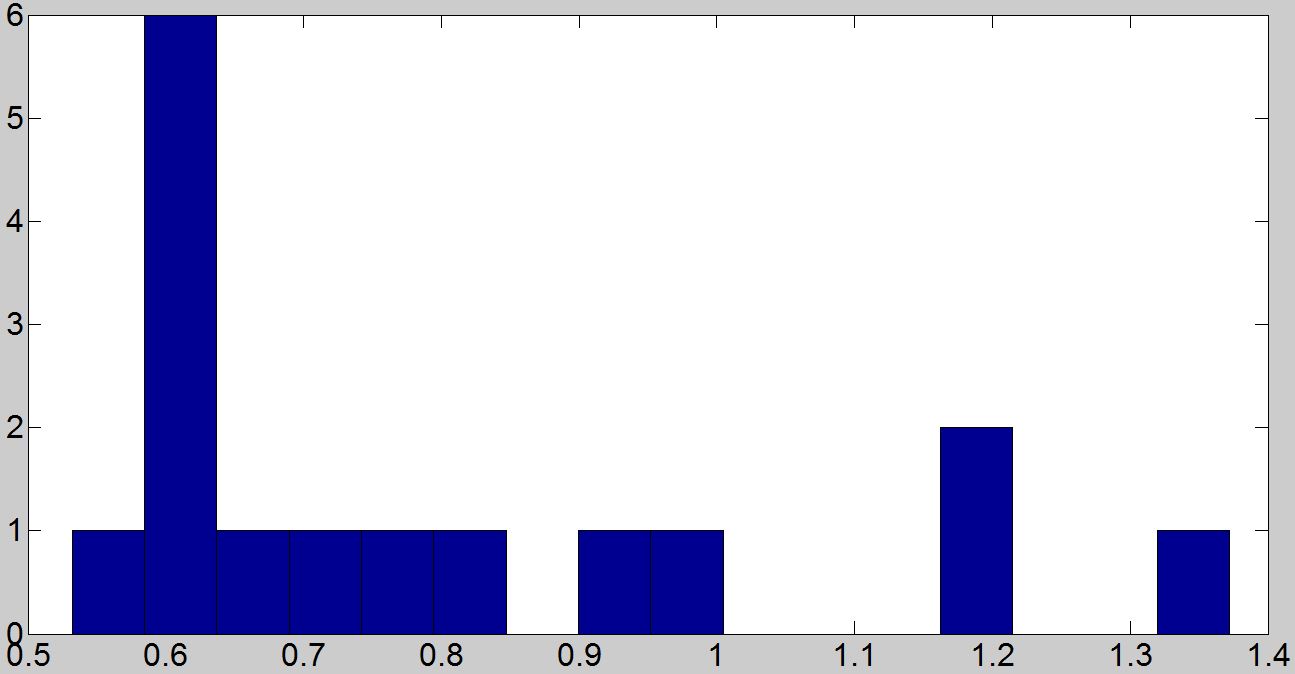
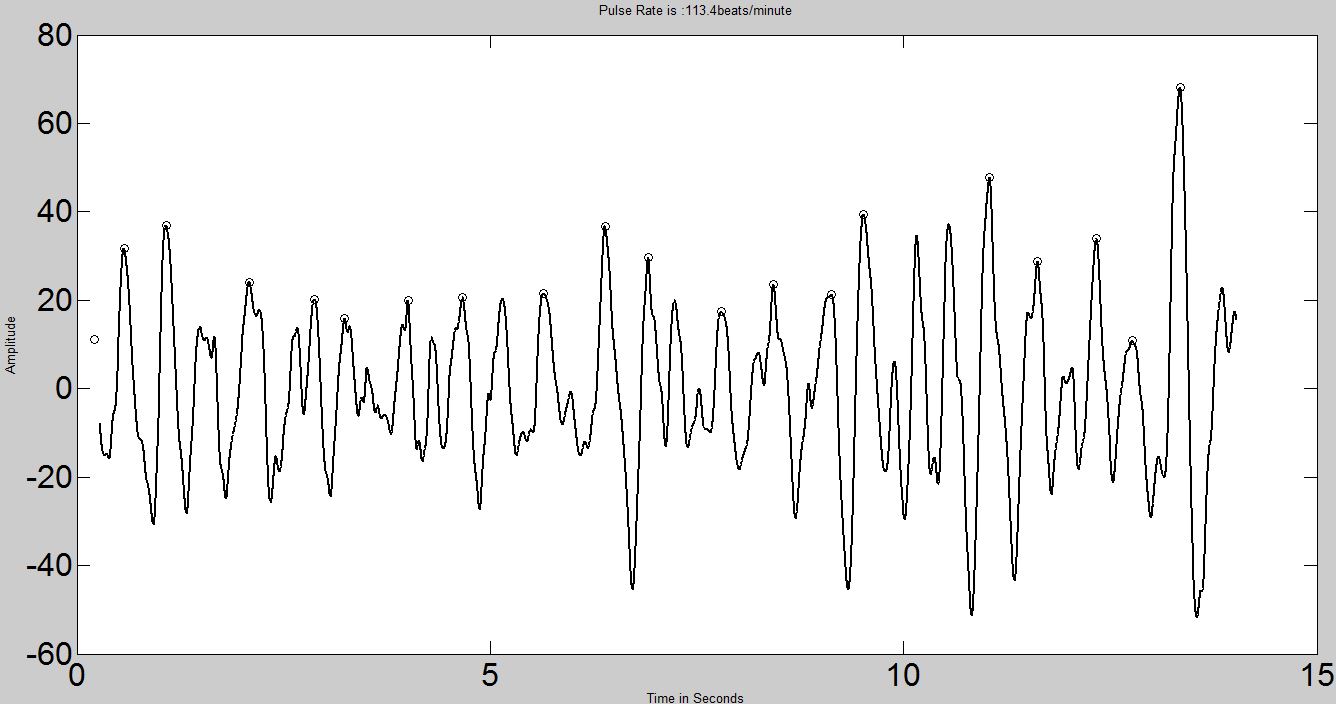


Figure 5.6 Histogram

b



a

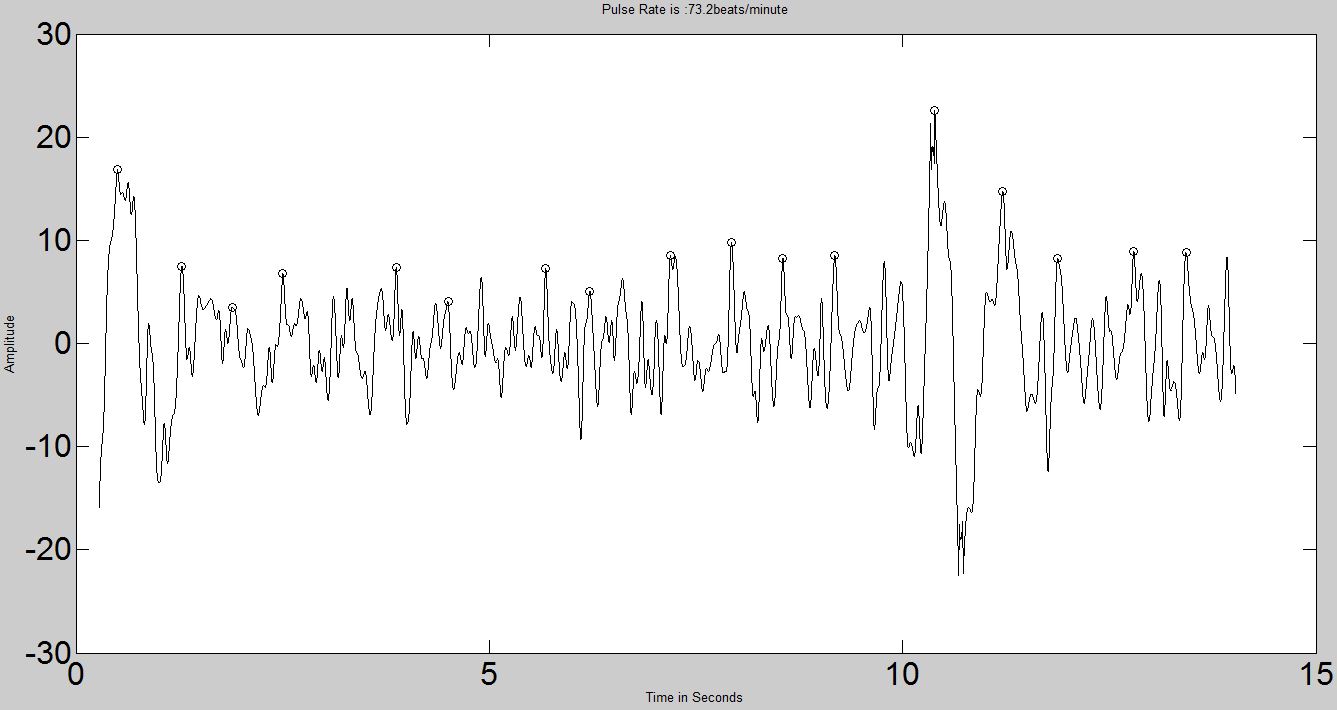


Figure 5.7 BCG Signal

b



a

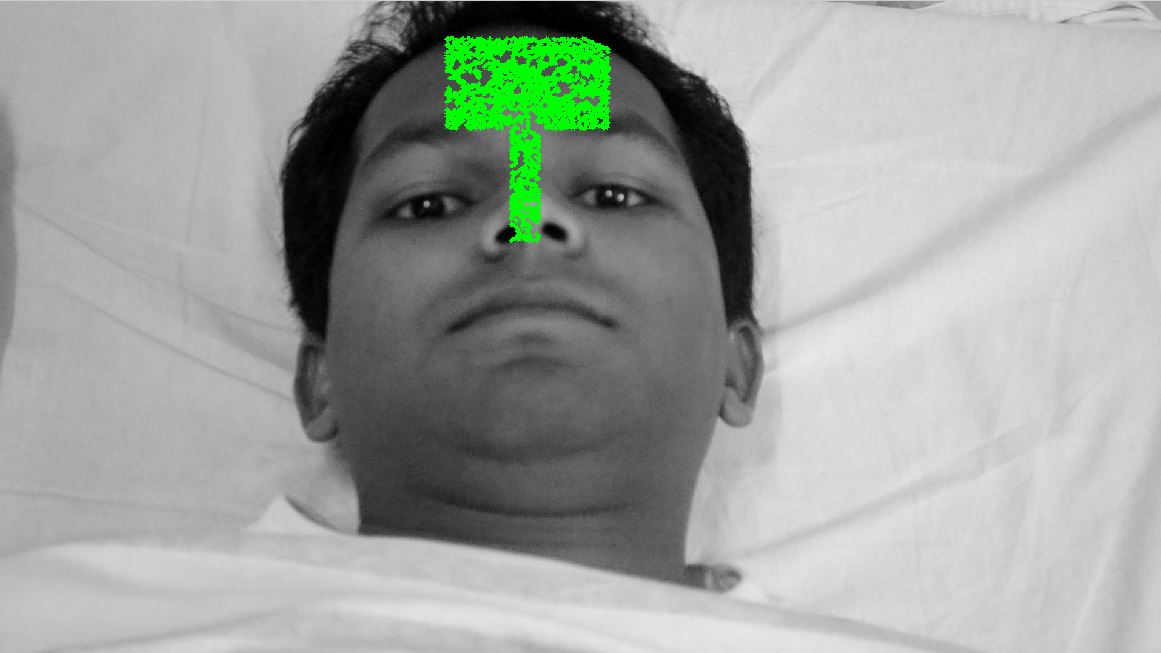


Figure 5.8

Figure 5.8 Snapshot of Subject

**5.** **Discussion**: We successfully recorded HRV and pulse rate. We performed our experiment with 12 subjects (10 male , 2 female) and achieved very satisfactory results with mean error of 0.96% in measurement of average pulse rate. We are also getting encouraging result for Beat length distribution, which could be ensured by statistical measures Mode and standard deviation. Mode is ensuring that we are getting good count for beat length corresponding to average pulse frequency. Standard deviation is ensuring us about beat length distribution with very low value. Since all our subjects are healthy that's why low standard deviation value is meaningful. For some cases we are getting large deviation in HRV values, it could be because of three reasons. First reason is we are recording only 30 frames/second whereas traditional ECG machines records signal with at least 128Hz sampling frequency and cubic Spline is able to address this issue partially. Second reason is filtering and component analysis technique are unable to remove involuntary motions. Third reason is tracking visual patterns which can be affected by non-uniformity of light. For getting pulse information from face I need to track unique features on face. To get good tracking results these features should be unique. But unique features like corners are very rare in most of the cases. This problem can be solved by two means first put some markers on face. We concluded above reasons for error in quantitative measurements. Unobtrusive and Non-Invasive characteristic of Ballistocardiography directs towards future where this technique could have application in Video surveillance, Lie detection, software or interface assessment, in heart monitoring of severely burn patients, with more sophisticated filtering, tracking and analysis techniques to detect and remove involuntary movements and other unwanted motions. HRV is very simple and informative parameter, good understanding of HRV in relation with Nervous system is good predictor of CVD and Heart functioning.

[1] NASA, “Ballistocardiography - a bibliography,” *NASA SP-7021*(*FAA AM 65-15*), September 1965.

[2] W. R. Scarborough and B. M. Baker, “Ballistocardiography - appraisal of current status,” *Circulation*, vol. 16, pp. 971-975, 1957.

[3] R. S. Gubner, M. Rodstein, and H. E. Ungerleider,“Ballistocardiography - an appraisal of technic, physiologicprinciples, and clinical value,” *Circulation*, vol. 7, pp. 268-286,1953.

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