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A Computer Vision Solution to Driver Fatigue

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Degree: MSc Intelligent & Adaptive Systems

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Statement of Originality

This report is submitted as part requirement for the degree of Intelligent & Adaptive Systems at the University of Sussex. It is the product of my own labour except where indicated in the text. The report may be freely copied and distributed provided the source is acknowledged.

Signed:

Acknowledgements

I would like to thank everyone who has offered me support over this last year, particularly to the doctors, surgeons and physiotherapists who are committed to see me walk again after a sudden and serious skiing accident. To my housemates and family members for providing me with all the additional care I've needed ever since. To all my fellow Sussex Snow committee members, for taking the burden of running Brighton's largest society off my shoulders during the critical final push to submission day. And of course to my technical supervisor, Dr. Chris Thornton, for his unrivalled patience, experience and guidance he has been able to offer me during the course of this project.

Abstract

In this study we demonstrate the powerful life-saving potential of modern computer vision technology when applied to the ongoing problem of fatigued drivers drifting off to sleep at the wheel, using just a USB webcam. Whilst our work serves primarily as a proof of concept of what can now be achieved at costs that significantly undercut anything presently available on the market that shares the same purpose, we do also go on to discuss methods in which this approach could be taken from prototype to fruition as a consumer-ready product.

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1. Introduction

1.1 Motivation

According to The National Highway Traffic Safety Administration [1], the primary cause for a conservatively estimated 100,000 police-reported crashes each year is driver fatigue. This accounts for $12.5 Billion in monetary losses, 71,000 injuries and 1,550 deaths, all of which are easily preventable. The Governors Highway Association [2] estimates these same figures to be 328,000 crashes, $109 Billion in damages, 109,000 injuries and 6,400 deaths in the US alone. This level of uncertainty is because drivers are reluctant to admit to the authorities if they were tired or even asleep at the time of an incident. Additionally, the crash itself would have also removed most of the symptoms of fatigue, leading to all official figures to be gross underestimations; hence the best figures we have are hardly exact. Regardless of the specific figures, there's no doubt that lives are being needlessly lost and something needs to change.

Studies have shown that the detriment to ones performance after 17 hours without sleep can be equated to a that with a blood alcohol content (BAC) of 0.05%, which is the legal limit in Scotland, whilst 21 sleepless hours roughly equates to a BAC of 0.08% [3] [4] [5], which is the limit for the rest of the United Kingdom. There are numerous laws in place to prevent the use of automobiles whilst your senses are in any way inhibited as a result of drugs or alcohol, but as of yet there are no applicable laws in place if that same level of inhibition is a result of fatigue.

There is currently no way to objectively quantify tiredness on the roadside, as we can do so for alcohol consumption with a Breathalyzer. Methods of measuring fatigue, such as the Phychomotor Vigilance Task (PVT) take 10 minutes to complete, and it has been shown by S. Loh et al [6] that motivation and the temporary adrenaline spike that is likely to be present can counteract the mal effects of up to 36 hours of no sleep, making them unfit for this purpose. I therefore believe the answer lies in the implementation of safety features as opposed to strict regulation. In the UK, car manufacturers have been required by law to install seatbelts since 1965, but these laws have not at all progressed in line with the progression we've seen in consumer technology. Even Tesla, the company that produces the most technologically advanced commercially available vehicles uses a very primitive system of a weight sensor in the steering wheel as their solution for drowsy driving prevention. With today's technology, feats that would have sounded like sci-fi only a few short decades ago could now be carried out by a hobbyist, and I believe this is where the solution to our problem lies, and if proven successful, laws should be updated to reflect this.

1.2 Project Aims and Objectives

Our primary objective is to save as many of these needlessly lost lives as possible, our system will be to wake up a driver should they be in danger of falling asleep at the wheel. Unlike a seatbelt, which only comes into action once something has already gone seriously wrong, our system will be able to pre-empt accidents, stopping them from happening in the first place. I must be clear that this is in no way intended to replace seat belts as they are for very different purposes, but I believe a combination of both would be highly effective.

It will work by playing an alarm sound should the driver's eyes remain closed for more than a specified time interval (e.g 2-3 seconds) as to avoid sounding the alarm if the driver simply blinks. There will of course be a hardware aspect to this project, however since our solution must also be cost effective, this will be kept to a minimum, and the only sensor we will be using is a budget USB webcam with which we can apply the necessary computer vision techniques. The importance of keeping the cost down is so that our solution can be a viable addition to mass production vehicles whilst having a negligible effect on the price. Ultimately, I hope to be able to create a car safety feature that is comparable to the seatbelt, in that it has enormous life-saving potential, and arguably no real downsides.

2. Professional and Ethical Considerations

Since testing and developing my project involves no human subjects or participants other than myself, it raises no legal, social, political or ethical issues for which I need to seek approval. I will however ensure that all work is carried out with due consideration for the standards set by BCS – The Chartered Institute for IT. Below I have outlined the points within the code of conduct that held the most relevance to my project, and the corresponding steps I have taken or will take in order to ensure my recognised responsibilities are met.

2.1 Public Interest

- 1b) ***"Have due regard for the legitimate rights of Third Parties"***
  I will take great care to avoid any breaches of this by ensuring proper referencing is used throughout all sections of the project, giving credit to any third parties where any material of any form is used that is not of my own creation.

2.2 Professional Competence and Integrity

- 2c) ***"Develop your professional knowledge, skills and competence on a continuing basis, maintaining awareness of technological developments, procedures, and standards that are relevant to your field."***
  My desire to further my knowledge is one of the key driving forces behind this project, I'm eager for any opportunity such as this to refine or acquire new skills. My awareness of any relevant developments is maintained by the background reading and research I'm undertaking around the subject, whether it be for work or as a hobbyist.

- 2b) ***"Ensure that you have the knowledge and understanding of Legislation and that you comply with such legislation, in carrying out your professional responsibilities"***
  I have familiarised myself with any applicable laws, statutes and regulations surrounding the project, including those concerned with copyright infringement, and at no point will I overstep any of them.

- 2e) ***"Respect and value alternative viewpoints and, seek, accept and offer honest criticisms of work"***
  This is arguably the most important part of a learning process. I will never disregard another person's viewpoint, nor will I overlook any form of constructive criticism, particularly as I am conscious that my views on my own solution may be subject to a degree of intrinsic personal bias, making its shortcomings more visible to others than they are to myself. In the case that I am the one offering such criticisms, I will of course exercise appropriate due diligence for the benefit of our scientific community as a whole.

- 2f) ***"Avoid injuring others, their property, reputation, or employment by false or malicious or negligent action or inaction"***
  This will be fully adhered to by ensuring the test environment is safe, strictly controlled and clear of any potential hazards, and all surroundings will be taken into consideration at every stage of the testing. Any tests carried out in an actual vehicle will be done whilst stationary and safely clear of any public roads and other moving vehicles.

2.3 Duty to Relevant Authority

- 3a) ***"Carry out your professional responsibilities with due care and diligence in accordance with the Relevant Authority's requirements whilst exercising your professional judgement at all times."***
  As my project supervisor and relevant authority, Dr. Chris Thornton has given me the freedom to take this project in whichever direction I see fit, for which I will of course exercise due care, diligence and my professional judgment at every step. We remain in frequent email correspondence to ensure any requirements he may have are satisfied.

3. Related Work

I will divide this section in to two distinct parts, the first shall divulge works relating to the underlying techniques and methodologies I wish to employ to create my program, whilst the second shall investigate solutions that are related to mine in the respect that they have the same objective.

3.1 Scientific Foundation

My initial thought when tackling the computer vision task at hand was to make use of an artificial neural network in a similar fashion to the one employed by the DataFlair team [7] when creating a similar program, that is, to classify eyes as open or closed once located.

Although computational models for neural networks have been around since McCulloch and Pitts' 1953 publication [8], it wasn't until the proposition of Fukushima's Neocognitron [9] in 1979 that these methodologies were applied to a task of image processing. This bridged a significant gap in the domain of problems to which ANN-based solutions could be implemented – the amount of real-world problems they could now theoretically be applied to was almost limitless with the option of taking a visual stimulus as input, which is the primary sense relied upon for countless real-world tasks such as this one. The Neocognitron is a multi-layered artificial neural network for pattern recognition, namely handwritten character recognition, and would later inspire convolutional neural networks.

As of more recently, deep convolutional neural networks can now be credited with tremendous advancement in a multitude of computer vision tasks. In 2011 for the first time, one such approach [10] was able to perform an image recognition task to a superhuman standard, achieving a greater degree of accuracy than human participants. With the task of that specific example being road sign recognition, the variety and complexity of computer vision tasks at which ANN's are able to outperform us has only been on a steady increase since, making them a very suitable candidate for our problem.

In terms of the object recognition required to locate our facial regions of interest (ROI), I made the decision to avoid deep learning approaches as they are computationally expensive, and this added complexity can lead to deployment issues in production systems, as well as the added caveat of needing large volumes of training data.

In 1986, a patent submitted by McConell [11] described techniques that would later be popularised by Dalal and Triggs in their seminal paper "Histograms of Oriented Gradients (HOGs) for Human Detection" [12]. In this paper their HOG approach was shown to outperform Scale-Invariant Feature Transform (SIFT), the previous front-runner proposed by Lowe [13], by an order of magnitude. Methods based on Haar Like features has also been outshone to a similar degree, and in their recent comparative analysis, Chauhan et al [14] substantiated this by exhibiting the high execution time of these approaches, making them less suited than a HOG method for our project. It's important to note that HOG descriptors themselves are not tied to any particular machine learning algorithm, Dalal and Triggs [12] found their success when using these HOG descriptors as features in a Support Vector Machine (SVM) classifier.

The ideology behind support vector machines is not such a new concept, it was first conceived in 1962 by Vapnik and Chervonenkis [15], and published two years later. This was further developed In 1992 Vapnik et al [16] when they proposed a way to create non-linear SVM classifiers by mapping inputs in to a higher dimensional feature space with what is called the Kernel trick, where a maximum separating hyperplane can then be found. For use in conjunction with the HOG feature vectors as per our project requirements, we need only use a linear SVM.

3.2 Similar Systems

3.2.1 Embedded Systems

Considering the severity of the problem posed by drowsy drivers, it’s surprising that similar systems to that which we want to produce aren’t already more commonplace, or even obligatory. The first such system was released by Volvo at the end of 2007, coined Driver Alert Control, and was aimed at distracted drivers and drowsy drivers equally. It worked by using data from a front-facing camera that would calculate the distance between the car and the road lane markings, as well as a sensor that would monitor the movement of the car, triggering if the driving was deemed to be ‘uncontrolled’. It’s important to note how far the field of computer vision has advanced since then, OpenCV for example was still very much in its infancy. Daniel Levy, the project manager for Driver Alert Control, can be quoted saying “we don't think that the technology of monitoring the driver's eyes is mature enough yet." during a 2007 press release [17] whilst justifying their chosen approach.

Another such system would be that introduced by Nissan, labelled their Driver Attention Alert System (DAA) [18]. This system also differs from ours fairly drastically, the key reason for this being the method in which it receives its input from the driver; rather than doing so via a camera, it makes use of steering angle sensors within the steering wheel. During the first few minutes of each drive it establishes a baseline snapshot of driving patterns, which is then continuously compared to subsequent patterns throughout the drive. Logic is used to reduce the chances of false positives caused by events such as lane changes, sudden braking, or changes in road conditions, although the specific nature of this logic is something they don’t seem to disclose publicly. Should the car be travelling above a threshold speed, and an irregularly high frequency of erratic corrections are detected, feedback is given to the driver in two key ways; an audible chime is played, as well as a visual display on the dashboard of a coffee cup with an accompanying message advising the driver to take a break. Audi, Mazda and Mercedes-Benz all have equivalent systems, using the same underlying principles, but under different names of course. The intricacies of the logic employed are also of course unique between companies.

3.2.2 Standalone Solutions

Similar systems to that which we want to produce come not only in a select few models of car by certain brands, but there do exist a few standalone devices for the same purpose. The key advantage of these systems is that they can of course be retrofitted to older vehicles that are already out on the road. The Anti Sleep Pilot (ASP) is prominent example, it comes in the form of a small circular device (pictured below in Figure 1) that is stuck to the dashboard. Upon the first use, a personal risk profile is established through a short test, the drivers current fatigue level is also input at the beginning of a drive. The drivers fatigue level is then continuously calculated and displayed by the bar on the left. Alertness is maintained and partly calculated by periodic reactive tests, in which the driver must touch the device as soon as indicated, obviously slower reaction times are indicative of a more fatigued driver. Warnings are also feedback to the driver in the form of audible and visual feedback. We must bear in mind that this device was the first of its kind, dating back to 2011 when technology was not where it is now, but even so, there are some clear limitations to its practicality which I believe can be improved upon. It carries a very high price tag of £130, and most (if not all) of the functionality it provides could now be done with a smartphone application. The occasional alertness tests could also be seen to be slightly distracting, and I question its accuracy considering its limited sources of information, that is an internal clock, accelerometer, GPS location and limited user input.

Figure 2 - Anti Sleep Pilot [25]

Figure 1 - Vigo Bluetooth Headset [26]

The Vigo Bluetooth Headset is a slightly more modern device with the same objective, it comes in the form of an earpiece that extends round towards the wearers eye. The extended portion measures variation in the user’s blinks, whilst the body houses a precise 6-axis accelerometer and gyroscope to monitor head movement. Feedback is again provided audibly, as well as through flashing lights, but Vigo can also combat fatigue by calling a loved one as well as vibrating. In terms of its downsides, it carries a substantial price tag of approx. £100, and it has received more 1-star reviews on Amazon than any other rating. According to these reviews, the primary reason for this seems to be that it’s unable to monitor the eye of users with a larger head, certain users have also reported it to be uncomfortable if worn for extended periods of time.

4. Requirements Analysis

First and foremost, I want to highlight that our prototype will largely serve as a proof of concept for the widespread implementation of similar systems. In an ideal world I would create a standalone product as described in the previous section, as whilst some newer cars are now being produced with similar embedded systems, these account for a very small proportion of cars on the road (the average age of cars on the road in the UK is over 8 years old [19] which pre dates the overwhelming majority of these systems), however due to limitations concerning my available budget and resources, this will not quite be possible. I will however create a working prototype, and although it will not be market-ready, I will describe a few methods in which it could be taken from concept to being consumer-ready.

4.1 Practicality

Our solution will aim to remedy the key shortcomings of those that are currently market-available such as the ones outlined previously in section 3.2.2, the area in which I believe we can do this by the most significant margin, is the cost. The importance of this factor cannot be overlooked if the ultimate goal is to one day have this system or an equivalent in every vehicle worldwide. At the very minimum, our solution must undercut those described previously (<£100), and I will use the cost of a seatbelt and accompanying inertia reel as a goal, these can be expected to cost approximately £50 excluding a pretensioner, which in itself costs 3 figures. The logic behind this is of course to use the cost of one universally accepted safety device as a sensible point of reference whilst creating a new one. It's important to note that whilst the isolated prices of the vehicle-embedded systems described in section 3.2.1 are not publicly available, they only tend to be found on newer models of cars which likely also have other forms of intelligent driver assistance such as smart cruise control or lane keeping, both factors drive the overall cost of the car up, meaning these systems remain rather financially unavailable to a significant proportion of motorists.

For our project to be considered practical, it must also negate the other key downsides posed by the standalone solutions in the previous section, these tend to concern how user friendly the system is, and so this will be our other key focus for improvement. I see this to be a particularly crucial aspect as a significant proportion of drivers may not feel the need for such a device since they have managed so long without one, and therefore any minor inconvenience caused by it could serve as sufficient justification for not using one. I believe an almost definite potential cause of this to be if our system allowed for false positives, resulting in obnoxious and loud alarms sounding when not necessary, and so the risk of false positives must be kept to an absolute minimum at all costs. Because of this, the system will only activate once the vehicle is travelling above a threshold speed (e.g 30mph), as the overwhelming majority of accidents caused by fatigue occur on higher speed limit roads that tend to be long and straight, where the driver isn't kept stimulated by frequent features such as traffic lights, junctions and roundabouts.

As for the reported problems with the Vigo Bluetooth Headset; comfort will not be an issue with our project as there is no wearable aspect to it - all information needed will be collected from a camera aimed at the user, and it should work regardless of the users head size for this same reason. As for the Anti Sleep Pilot, there will be no need for a lengthy set up test to establish a risk profile, nor will ours require the drivers attention for periodic alertness tests, and although I don't have the means to test it, I hope ours to achieve at least, if not more effective results than the Anti Sleep Pilot. I want to highlight what I said at the end of section 1.2 - we want to create a program that has significant lifesaving potential without inconveniencing the user, at a low cost, such that there is little reason to not have it installed in a car.

4.2 Hardware

The hardware aspect to the project must be kept to a minimum in order to keep the overall cost as low as possible. The only piece of specialist equipment that I will be using for this project is a cheap non-branded USB webcam retailed on Ebay for only £10. Although an infrared camera and light source would be ideal for this project as to provide night-vision capability to cater to the environments in which drivers are most likely to fall asleep, this webcam is all I have access to, however it provides all the functionality necessary to serve as a proof of concept, as well as requiring no setup or installation – it is simply ‘plug and play’ on any computer I have tested it with. Please note that the addition of an IR camera and light source would not compromise our aim to keep the overall cost at an absolute minimum, units containing both components can be purchased for less than £10 [20].

4.3 Software

I will implement the programming aspect of the project in Python, as it a programming language with which I have previous relevant experience. It also has support for packages such as OpenCV and Dlib that I believe to be well suited to the task at hand. Additionally, python scripts can be easily ported on to and run on Arduinos such as the Raspberry Pi should we go on to develop a standalone prototype.

4.3.1 Face & Landmark Detection

In order to track a user’s eyes, we must first detect their face as whole. For the reasons outlined in section 3.1, I will be using HOG descriptors as feature inputs to an SVM classifier for the purpose of face recognition.

The first step in calculating a Histogram of Gradients descriptor is to independently calculate the gradients in the *x* and *y* direction using these two filters:

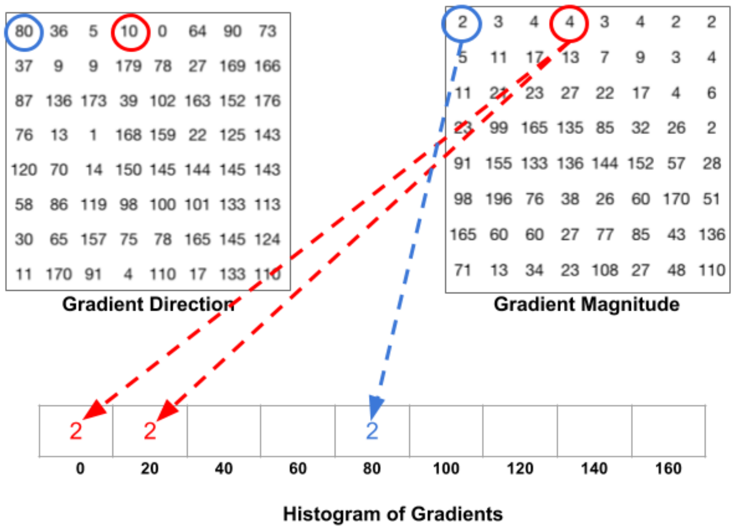
$$\begin{bmatrix} -1 \\ 0 \\ 1 \end{bmatrix} \quad \begin{bmatrix} -1 & 0 & 1 \end{bmatrix}$$

We can then calculate the gradients direction and magnitude at every pixel using the following two formulae respectively:

$$\theta = tan^{-1}\left(\frac{g_y}{g_x}\right) \qquad g = \sqrt{{g_x}^2 + {g_y}^2}$$

The image is then divided in to 8x8 pixel cells, for which a histogram of gradients will be created for each, this creates robustness to noise. To do this, the 64 magnitude values are cumulatively binned between 9 different bins corresponding to unsigned direction values from 0 to 180 degrees, in 20-degree increments.

Figure 3 - How magnitudes are proportionally split between bins in accordance with their direction [27]



Above in Figure 3, you can see how the assignment process of cumulative magnitudes into the corresponding bins works. For example, the 2 (circled in blue) has a direction of exactly 80 degrees, and so 100% of its magnitude is assigned into the appropriate bin. The number circled in red however has a direction that lies exactly between two bins, hence the proportional 50:50 split of its magnitude between them. Each bin represents one bar of the histogram which has now been formed per 8x8 pixel cell. In order to make this approach insensitive to lighting, normalization is required, this is done over every 2x2 cell (16x16 pixel) area. Each histogram within the area being normalized is concatenated to form a one dimensional vector containing 36 values, and then dividing by its L2 norm gives its unit weight in which scale has been removed. The final HOG feature vector for the entire image can then be calculated by concatenating all of the 36x1 block vectors.

For the purpose of object detection, we must calculate HOG feature vectors for a large sample of positive images, that is ones that do contain a human face, as well as a large sample of negative images that do not contain a face. These can then be used to train a SVM classifier. When testing an image, the SVM uses a sliding window approach at various scales - this window starts at the top of the image sliding from left to right, before making its way down the image. The HOG descriptor is calculated for each window, and a classification is given. There will almost certainly be false-positives, these incorrectly classified HOG descriptors are recorded before being used to retrain the classifier in a process known as hard-negative mining. Windows that detect a face with a sufficient probability, become the bounding box for that ROI (region of interest), overlapping windows are removed with a technique called non-maximum suppression.

Dlib is an open source toolkit originally developed in C++ that specialises in machine learning tools and algorithms for industry as well as academia. Fortunately for us, it also has a Python API, and so we will be making use of their pre-trained HOG face detector for the purpose of our project. In addition, Dlib also offers a tried and tested pre-trained 68-point facial landmark predictor; this estimates and tracks the co-ordinates of facial landmarks (e.g nose, eyes, mouth) using a set of 68 *(x, y)* co-ordinate points.

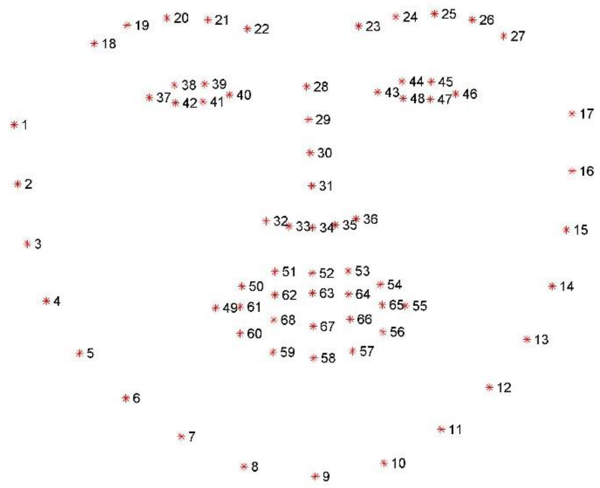


Figure 4 - Dlib's 68-point facial landmark shape predictor [28]

Above in Figure 4, you can see the points mark-up that was used by the Intelligent Behaviour Understanding Group (iBUG) to annotate their 300-W dataset upon which Dlib's facial landmark predictor was trained.

4.3.2 Eye Aspect Ratio (EAR)

Dlib's facial landmark predictor described above was the deciding factor for me to abandon my original idea of using a machine learning based approach to classify eyes as open or closed, in favour of taking a simple measurement proposed by Soukupová and Cech in their 2016 publication [21] called the Eye Aspect Ratio, or EAR. Using a sub-group of just the 6 points (*$p_{1\text{-}6}$*) needed to represent an eye from Figure 4, the equation for the eye aspect ratio is as follows:

$$EAR = \frac{\|p_2 - p_6\| + \|p_3 - p_5\|}{2 \times \|p_1 - p_4\|}$$

One key property of the Eye Aspect Ratio is that it remains fairly constant whilst the eye is open, but rapidly drops towards 0 as soon as the eye begins to close.

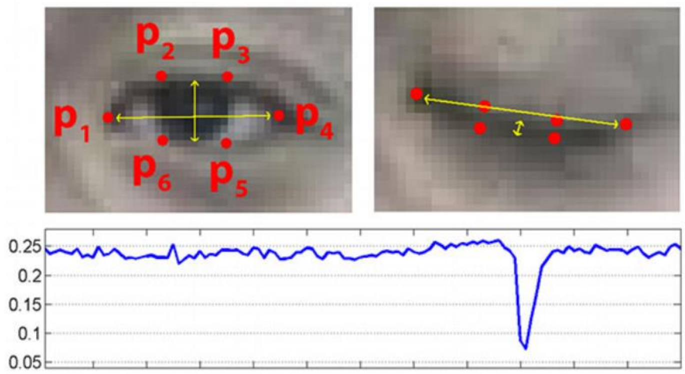


Figure 5 - How EAR changes over time with a blink [21]

Above in Figure five, taken from Soukupová and Cech's publication, you can see how an otherwise fairly constant EAR value plummets towards 0 as the eye closes. Using this principle and simple calculation, we will be able to monitor for situations in which the detected EAR drops below a given threshold, and remains low, as this would be indicative of a drivers eyes staying closed (or nearly closed) as they likely doze off, as oppose to simply blinking.

Where this EAR threshold is set is crucial to the functionality of our system. It could be argued that this is one potential downside of this approach over a machine learning one – whilst a classifier may identify an eye as open or closed irrespective of the following factors (given sufficient training data), an EAR can be influenced by user specific variables such as the angle of their head, where the camera is mounted in relation to the users face, how reclined the driver's seat is, and even the ethnicity of the driver. In other words, it would not be possible to globally distribute a 'one size fits all' threshold for all users. The redeeming factor of this however is that we are working with continuous data as opposed to discreet classifications, this data is more descriptive which can allow for added functionality such as waking a driver as they are drifting off to sleep, as opposed to only after they have fallen asleep.

In order to solve this thresholding problem, the system must calculate a threshold that is specific to the user and the environment within which it is installed. Please see the pseudocode below for my proposed solution of an initial calibration phase that requires no input or action from the user in order to preserve user experience, and is carried out automatically each time the system starts up, in practice this would be each time the driver exceeds the minimum threshold speed at which it is activated **[justify?]**. Please note those variables written in italics indicate numerical constants.

```
If currentFrame < calibrationDuration
      calibrationEARs.append(currentEAR)
Else If Not thresholdCalculated
      EAR_threshold = average(calibrationEARs) * thresholdPercentage
      thresholdCalculated = True
```

As you can see, the concept is fairly simple. For the first *x* frames, denoted by the integer stored within *calibrationDuration*, the users resting eye aspect ratio is calculated and appended to a list. Once this calibration duration has expired, all of the stored EAR values are averaged, before being multiplied by a fraction *(thresholdPercentage)* to give the final EAR threshold below which the alarm will be triggered if at any point the current EAR remains below it for a sufficient amount of time. For example, with a *thresholdPercentage* of 0.75, the EAR threshold will be set to 75% of the user's average resting EAR over the calibration period. This value may seem high, but recall that one property of the EAR measurement is that it remains rather constant until the eye begins to close, at which point it drops dramatically. Nevertheless this is a variable that will need to be tuned and optimised during the testing phase.

I considered taking equivalent measurements of the mouth in to consideration, the idea being to look for other earlier signs of fatigue such as yawns, much like what was done by Zhong et al in 2019 [22], however I decided against it for a couple of reasons. Firstly it would be very challenging to distinguish between yawns and other actions that require a wide open mouth such as singing along to the radio, additionally, we want to create a system that provides arguably no inconvenience to the user whilst driving, and individual yawns often do not imply that one is moments away from falling asleep, or fatigued to the point that their life is in danger (yawns can be contagious for example [23]). The resultant false positives and unnecessary prompts delivered to the driver would result in a less user-friendly experience and may well lead to the user disabling the system. With the EAR measurement on the other hand, even if our assumption about the users eyes being closed as a result of fatigue is incorrect, it is irrelevant, as a drivers eyes must remain open at all times with the exception of blinking, and so a prompt or alarm should be sounded regardless.

5. Results

As mentioned in the introductory paragraph of section 4, this is merely a prototype to serve as a proof of concept of what can be achieved with modern computer vision technology at an incredibly low price point, therefore the lightweight computation is simply being carried out on my laptop as opposed to within a single device that with sufficient funding and development, could be no bigger than the webcam I used. In Figure 6.1 below you can see the first hardware configuration I tested, with the camera mounted directly in front of the drivers face above the steering column. Figure 6.2 shows the camera's viewpoint from that position, as well as the programs interface. Although this would not be displayed to the user, it provides some very useful feedback for debugging purposes such as the current Eye Aspect Ratio, the user-specific threshold, and the bounding box and contours of the drivers face and eyes respectively as to clearly show if a face (and specifically the eyes) has been detected or not.

Figure 6.1 - Hardware Configuration Highlighting Camera Location

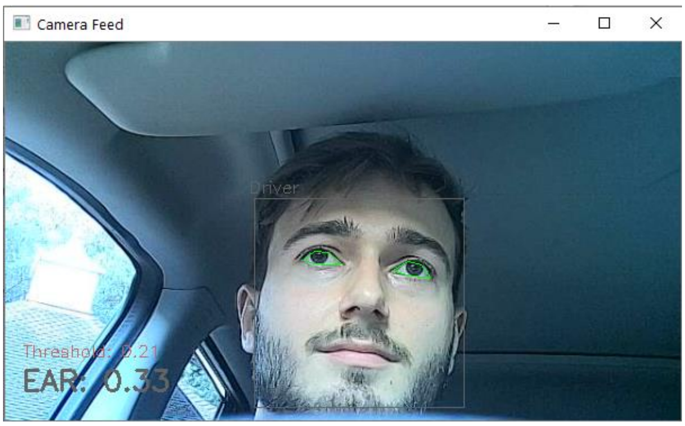


Figure 6.2 - Camera's Viewpoint

As a quick disclaimer, you will notice the car door remains open in any images taken from the camera's perspective, this is because of my recent disability - my right leg is fastened in to a brace, unable to bend and therefore fit in to a car seat.

Figure 7.1 - Hardware Configuration Highlighting Alternative Camera Location

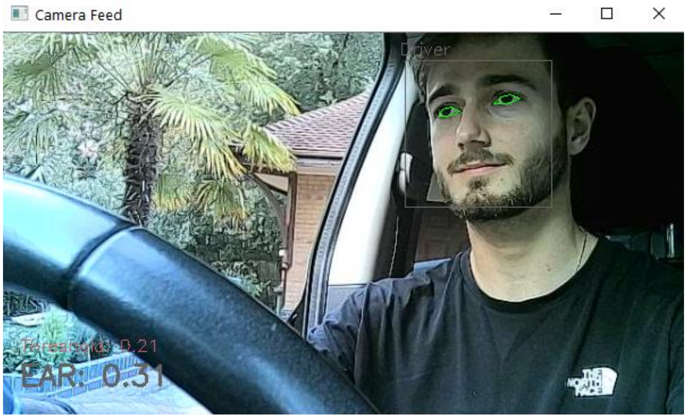


Figure 7.2 - Camera's Perspective

Above in Figure 7.1, you can see an alternative hardware configuration, with the camera instead mounted more centrally on the dashboard. Although the system is fairly insensitive to its specific mounting position, the latter set-up is more optimal because as you can see in Figure 7.2, the increased distance between the camera and the drivers face provides a greater area within which the driver's face can move, whilst still remaining clearly visible to the camera. There is of course a limitation to the benefit brought by increasing this distance – move the camera too far back and the front of the dashboard begins to obscure the view, and the further across to the left of the dashboard it is moved, the less the driver can turn his head to the right before their eyes can no longer be tracked. One possible way around this would be to use a camera with a wider angle lens, although it is not necessary for the functionality of the system, since drivers heads typically stay in the same position such that they have the use of their mirrors.

Figure 8 - Camera's Perspective Whilst Alarm is Triggered

Above in Figure 8, you can see what happens when the currently calculated eye aspect ratio falls below the calibrated threshold for longer than is permitted. As I mentioned earlier, this display wouldn't normally be visible to the driver as to not direct their attention away from the road, not to mention the needless addition of a screen would result in a significant bump in the overall cost, and so a loud and continuous alarm is sounded that persists until the EAR once again returns to a level above the calculated threshold. The amount of time that the EAR is permitted to dip below the threshold before triggering the alarm is another important factor, of course blinks should not raise an alarm, however there is no permissible reason for the drivers eyes to ever remain closed for longer than a slow blink of about 1 second long, and therefore this works as a reasonable time limit.

According to UCL researchers, a human blink lasts only 0.1 – 0.15 seconds [24], and if you closed your eyes for just 1 second whilst travelling at the national speed limit (70mph), you would cover a substantial 31.3 metres in that time, so you may be wondering why there is a need for such a discrepancy, wouldn't the system be safer with a lower threshold much closer to 0.15 seconds? This is again to prevent false positives caused by imperfect fluctuations in the calculated EAR and the inevitable frustration and deteriorated user experience they would cause the driver. The preservation of user experience is so crucial as many drivers may feel as though they don't need such a system since they have survived for so long without one, therefore even the infrequent and mild inconveniences caused to them by false positives could be sufficient justification for them deciding against the use of such a system.

5.1 Trackable Range

Figure 9.1 - Successful Eye Tracking Maintained with Maximum Turn to Driver's Right

Figure 9.2 - Successful Eye Tracking Maintained with Maximum Turn to Driver's Right

In Figures 9.1 and 9.2 you can see the results when testing the trackable range of the eyes as the drivers head is rotated horizontally. In both figures my head is rotated to a position beyond what is safe to drive from, as I can no longer even see the road with both eyes, yet the eye tracking and EAR calculations are still functioning as intended. It must be noted however that whilst full functionality was maintained in both extreme cases, the calculated EAR values would fluctuate comparatively more so in the case that the driver is looking to the right (Fig 9.1) due to the increased angular distance between the camera and orientation of the driver’s head

Figure 10.1 - Successful Eye Tracking Maintained While Head Fully Lowered

Figure 10.2 - Eye Tracking Failed While Head Fully Raised

The results of testing the vertical trackable range can be seen in Figures 10.1 and 10.2. Much like with the results seen in Figure 9, once my head was lowered to the point where I would no longer be able to safely see traffic in front of me, the eye tracking and full alarm functionality was still maintained, as seen in figure 10.1. Figure 10.2 however depicts the only extreme case in which the eye tracking failed; with my head at the position pictured, I was still able to see out in front of the vehicle, yet the face and eye tracking would very intermittently alternate between working and not (pictured). The back of most drivers heads tend not to rest back on the headrest whilst driving, and therefore more often than not when falling asleep, driver’s heads tend to slump forwards in which case their eyes remain well within the trackable range. This is by no means a dismissal of this shortcoming, as it is entirely viable for a driver to fall asleep whilst leant back as pictured, and further experimentation is certainly required to get to the root of this problem.

5.2 Glasses

Figure 11.1 - Successful Eye Tracking Whilst Wearing Glasses

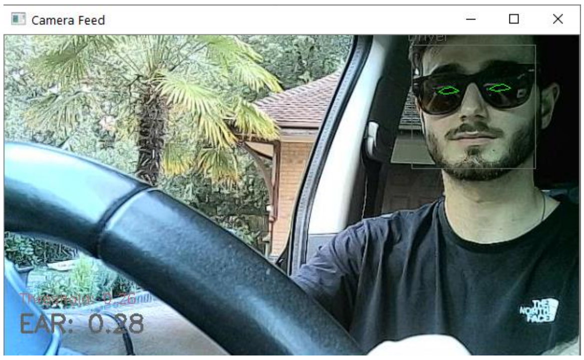


Figure 11.2 - Unsuccessful Eye Tracking Whilst Wearing Sunglasses

Figure 11.1 depicts the success we found whilst testing the system with prescription glasses, these particular glasses were multifocal -4.5 diopters which are very much on the stronger end of what is available. The program’s functionality was not inhibited in any way, shape or form, and given the high strength of the glasses, I have full confidence that this would also be the case with any other prescription glasses. In Figure 11.2 we can see the camera's perspective whilst the driver is wearing sunglasses. Although at first glance this screenshot may appear successful, as expected, the eye tracking was not functioning correctly despite the eye contours appearing to be drawn in roughly the correct place. In practice these contours, and so the estimated position of the eyes, would fairly erratically jump around the region of the glasses lenses. Enough of the face is still visible for dlib's HOG feature vector and SVM-based face detector to identify that a face is present, and therefore dlib's facial landmark predictor is still able to estimate the positions of the 6 points that describe each eye relative to the points that are still visible such as those on the jaw, nose and mouth (see figure 4 for reference), however its accuracy is severely impaired due to the eyes not actually being visible. This means that although it can still estimate the position of the eyes with mixed success, it is unable to produce accurate Eye Aspect Ratio measurements, and therefore the eye contours consistently assume a fairly default shape meaning that no alarm is sounded even if the drivers eyes are completely closed behind the sunglasses. This result was to be expected given the very limited budget and hardware I had access to, but in section 5.1 we will discuss the significance of this as well as a potential solution that remains a point of further investigation that I am keen to pick up on given the proper equipment.

5.3 Distraction Prevention

In an attempt to branch out the functionality of the system to also cater to distracted drivers as well as those that are fatigued, I altered the code to also trigger the alarm if no face was detected at all.

Figure 12 - Altered System to Attract Attention of Distracted Drivers

You can see a positive result of this above in Figure 12 in which the alarm was triggered by me looking out the side window rather than forwards. This also remedied the shortcoming we identified in Figure 10.2, in which eye tracking failed when the drivers head was leant back too far. Whilst these (particularly the latter) are two fairly significant benefits, this added feature is by no means without its limitations. In terms of preventing distracted drivers, it only works within a very limited domain, such that the drivers entire head is turned sufficiently far that their face is no longer detected, which as we established earlier is beyond what is safe to drive from. This means that there is a zone (of head rotation) within which the driver cannot safely drive, yet their face is still detected and therefore no alarm is triggered. Additionally, due to the relative mounting position of the camera this only really works whilst turning to the right – when turning to the left the face remains detectable until well beyond what is safe and is only likely to trigger if the driver was turning to someone sat in the back.

Because of this I believe a more appropriate solution to resolving the issue of distracted drivers lies with the tracking of the driver's pupils, and therefore their gaze. In practice however this is rather complex to implement, as a drivers pupils do not stay locked on the road; there must be allowance for the driver to look to each side for both wing mirrors, as well as upwards for the rear view mirror, and even downwards for adjusting the air conditioning and radio for example. The specific angles and thresholds would again also vary and be specific to each vehicle, therefore adding to the complexity of the problem. When also considering the extensive opportunities this would create for false positives and how critical it is we keep these to an absolute minimum, I decided this to be out of the scope of my current project to combat the ongoing issue of fatigued drivers falling asleep at the wheel, however it very much remains a potential additional feature that deserves a project of its own.

After some testing I settled for a solution in which if no face is detected for more than a few seconds, then a gentle vocal alert is played saying "Please ensure you're focused on the road". Critically, unlike the alarm which persists until open eyes are detected once again, this alert is only played once as a form of damage control to the user experience. Additionally, the few seconds of delay before it is played means that if the user's face is in a position such that it is right on the boundary of what is trackable, and so the tracking continuously cuts in and out, then the alert will not play repeatedly in conjunction with each time tracking is lost – rather it will only play once when the tracking has been lost for a sufficient time interval. This also means the reminder will not be sounded repeatedly if there is a malfunction meaning faces are no longer tracked, such as damage to the camera lens. The system as a whole is also only activated once the vehicle is travelling above a threshold speed which prevents this alert from sounding unnecessarily if the driver is moving from their seat, or talking to passengers in the back whilst the vehicle is at a stop. Although the limitations regarding the effective prevention of distracted drivers outlined above are still valid, this is a 'better than nothing' additional feature that most importantly helps tackle the issue outlined in Figure 10.2, and critically preserves user experience by minimizing the chance of false positives. Since no face being detected only implies there is an error on the driver's part, rather than guarantee it as detected closed eyes do, it is appropriate that the given alert in this case is softer.

5.4 Low Light Performance

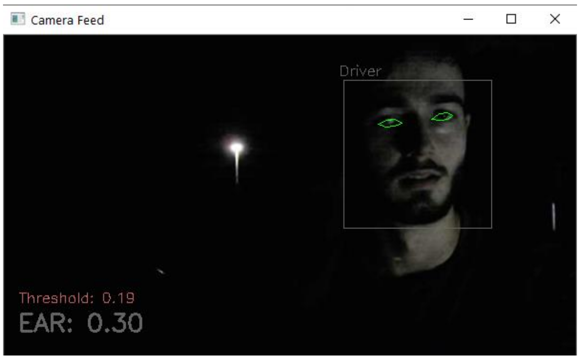


Figure 13.1 - Low Light Success

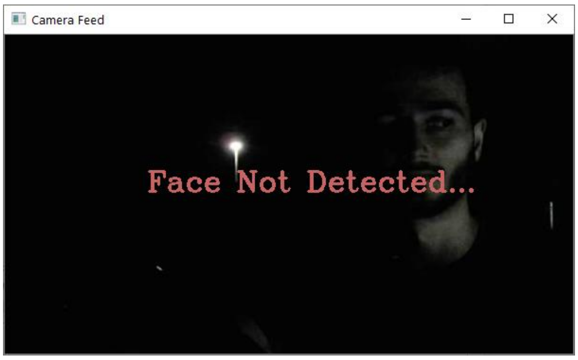


Figure 13.2 - Low Light Detection Failure

When tested in the low-light conditions of a night drive, much more akin to the environment that a fatigued driver is likely to be found in, the performance did suffer as expected. The limited light provided by street lamps was enough for detection and therefore EAR calculation to occasionally be possible, however it was far too inconsistent for the purposes of this program. As I mentioned in section 4.2 however, I knew this would be an issue with this specific implementation caused by nothing more than restrictions regarding what hardware was presently available to me. I tested this by executing the code on various infra-red portrait photos of varying quality to simulate the results had I had an infrared camera available, please see Figure 14 for the results.

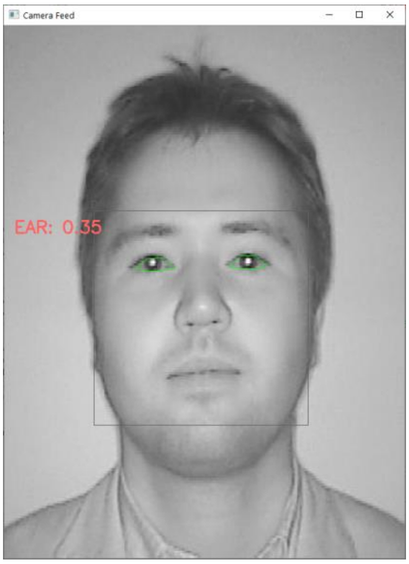


Figure 14.1 - High Quality Infra-Red Test
(Photo source: [29])

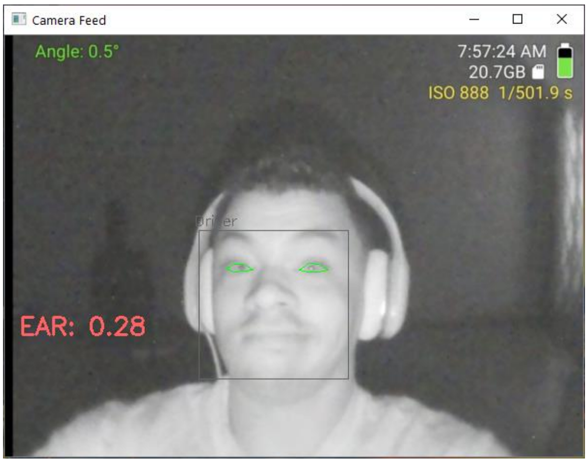


Figure 14.2 - Lower Quality IR Test, Overexposed Subject (Photo source: [30])

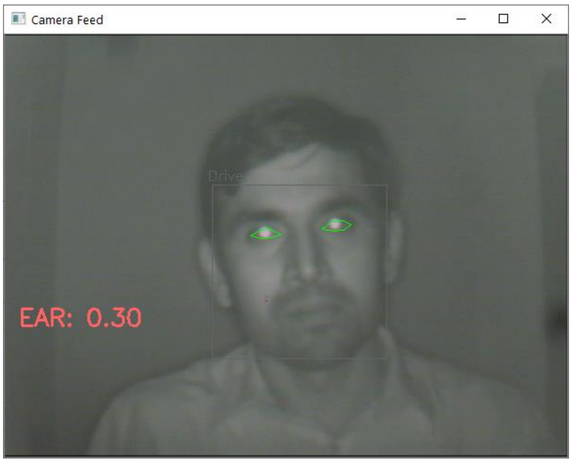


Figure 14.3 - Lower Quality IR Test, Dim Light Source (Photo source: [31])

As seen above, our implementation was successful on all infrared photos I tested it on. I ensured the photos varied in both quality and lighting, to cover a wider variety of conditions as to increase the likelihood of encompassing those that our system would produce given an infrared camera. The key drawback of IR cameras over their conventional counterparts is the loss of colour, however since we convert all images to greyscale as part of the pre-processing, this is of course not an issue. I do anticipate that if figure 14.3 were a video, the calculated EAR value would fluctuate more so than that for figure 14.1 due to the decline in resolution and lighting, however further testing would of course be required to validate this and assess if it would pose any issue. Regardless, I would suggest the incorporation of a 1080p HD infrared camera with this project, which would provide 2.5 times the resolution of figure 14.1 – the highest resolution photo above.

6. Areas of Potential Improvement

As outlined in the previous section, the key limitation of this first prototype lies with the equipment I had presently available. The performance of our webcam, and therefore system as a whole, suffers in the low light conditions that are present whilst driving at night. If not for strict funding limitations, I would have been able to invest in a 1080p HD infrared camera, with accompanying infrared light source, all for under £10 [20]. So the cost-effectiveness of this project remains highly viable. As mentioned earlier, the primary shortcoming associated with infrared cameras versus normal ones is the loss of colour in their images, however we convert each frame to greyscale as part of the pre-processing anyway, since colour is irrelevant for our purposes.

Another area in which this system or a similar one could be improved is in the form in which feedback is given to the user. Currently sound is relied upon to wake a sleeping driver, however in the unlikely situation that a driver is in a sufficiently deep sleep whilst loud music is also playing, the alarm sound is likely to be drowned out. Having the option to also deliver physical feedback to the driver would make for a more robust system. This would not be practical in a standalone device unless it is a wearable (which is an approach we have decided to avoid in order to preserve user experience), and so this suggested improvement is geared towards systems that are embedded within cars. Visual feedback should still remain at a minimum as to avoid any unnecessary distraction, however if the seat were able to vibrate in conjunction with the alarm, this would help negate the risk of a driver not responding to an audio queue for any reason. Vibrating the wheel would also help wake up a driver, however I believe this to be best avoided as to not compromise their control of the vehicle in any way. As far as the audio feedback is concerned, I think it could also be beneficial to offer the user a certain degree of customization to ameliorate their experience as much as possible. For example, the choice of different alarm tones, or a settings that would cause the volume of the alarm to start softly before increasing the longer the drivers eyes remain closed beyond the threshold, or even make the volume inversely proportional to the calculated EAR value, such that a gentle alarm is sounded after the user has remained past the threshold for the permitted period of time, and then the volume increases further as the EAR reduces, i.e. the more closed the users eyes become, the louder the alarm gets.

Another caveat we explored with the current implementation is that it doesn't work whilst the user is wearing sunglasses. I anticipate this will be less of an issue when using an infrared camera, since sunglasses are typically designed to block out ultraviolet wavelengths as opposed to infrared ones, although this is not universally the case. In these situations, however, we must remember that sunglasses are very rarely worn while driving at night, which is when a driver is most likely to be suffering from fatigue. Whilst comparatively unlikely, it is of course possible that a driver hasn't slept in an extended period of time and is driving in daylight whilst wearing sunglasses that do block infrared, in which case our proposed system will not work. It's important to remember that in this unique situation the driver is not disadvantaged any further by the system, so whilst this remains a point for future improvement, it in no way renders the system obsolete.

6.1 Bringing to market

Being just a prototype to serve as a proof of concept for what can be achieved at very low costs, our implementation obviously lacks on the design front. Should car manufacturers wish to adopt this methodology for much lower end cars than those that already have similar systems, the camera could be built in to the car in any rear-facing surface that has a clear view of the driver, resulting in something that is barely noticeable. In order for this approach to be developed in to a standalone product that is therefore compatible with the majority of vehicles that are already on the road, more stages of prototyping will be required to refine the design, but I do not anticipate it would be hard to create a device no bigger than a matchbox that is mountable to the dashboard.

An alternative method to bring such a product to market whilst keeping cost to an absolute minimum would be to utilise the driver's smartphone to carry out the processing, therefore negating the need for the device itself to be able to perform the necessary computation. Whilst implementing this as an app, or extra feature in navigational apps such as Google Maps or Waze, would work during daylight, their front-facing cameras do suffer in the limited light of night drives. A smartphone accessory however that consists simply of an small infrared camera and accompanying infrared light source, connected to the smartphone via a cable (since Bluetooth lacks the continuous bandwidth to steam video) could be mass produced at a very low cost. Night vision (infrared) camera modules that include a 1080p HD sensor as well as IR light source can be purchased for under £10 [20], so I believe it is more than possible to create such an accessory at costs that are marginal compared to any similar system on the market.

In terms of the distribution of such a product, I do anticipate that it may be difficult to motivate people who have never fallen victim to drowsy driving (who still make up the majority of the population, despite the ubiquitous nature of the problem) in any way to part with their money for a device that they would by no means deem essential; hence placing such a key focus on both keeping the cost as low as possible, whilst preserving the user experience as much as possible during all stages of development. Although the overall cost for such a device will likely climb beyond the sub £10 key component cost (£30 inc. Arduino to manage processing) due to the costs associated with the prototyping and development of such a product, this would not have to be the case given sufficient funding and investment. One example demographic that springs to mind who I'm sure would be interested is parents buying for their children as they begin to drive. However, provided that the cost can be kept minimal, I believe that the largest potential lies with large car insurance companies that could serve as major distributors for such a device – issuing a £10-£30 device to policy holders would be in their interest too as to reduce the amount of accidents, and therefore claims they must manage.

6. Concluding Remarks

We have created a program that, through the use of relatively modern computer vision techniques, has the potential to save the lives of multiple thousand motorists every year. We have demonstrated the suitability and effectiveness of these techniques in practice with regards to the task of awaking an overly-fatigued driver, and additionally we have gone on to describe multiple ways in which our proof of concept could be developed in to something very practical, as well as outline areas within which these ideas could be further developed for the benefit of all road-users.

Change on a global scale is something that requires time, and a lot of it. Although hard to pinpoint exactly, the original invention of the seatbelt pre dates the legal requirement to wear one (In the UK) by approximately 140 years. Even the modern 3-point seat belt as we know it today pre dated this legislation by over 3 decades. Whilst some may argue that the near-future is one full of autonomous vehicles, and so such a program will soon become obsolete, we are by no means there yet. Even with the huge technological breakthroughs needed to reach this goal, the transition period to driverless roads is one that will take enormous amounts of time on top of the development that is still needed. As bleak as it may sound, the fact of the matter is that thousands of people who are alive today will suffer an early death due to drowsy drivers, this is an inevitability, yet as we have shown - we have the technology available to prevent it right now.

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