B.Tech.- Project

on

# Track check in Helicopter using Image processing

Submitted by:

**Rahul Saini (2020ME10959)**
**Mansi (2020ME21031)**

**B.Tech Mechanical Engineering**

**Supervised by : Prof. Arpan Gupta**

**Signature of the supervisor:** ______________

**Mechanical Engineering Department**
**Indian Institute of Technology Delhi**

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# Contents

# List of Figures

# List of Tables

# 1 Abstract

Helicopters inherently exhibit various types of vibrations that can result in crew discomfort, structural fatigue, and safety concerns leading to potential accidents. Vertical vibrations, often stemming from blade misalignment or ”out of track” conditions, pose a significant challenge. This project aims to track vertical vibrations during blade tracking through image processing. The proposed approach offers a cost-effective and straightforward alternative to existing methods in the industry.

The method comprises several key steps, including image filtering, image thresholding, precise blade tip position determination, and the conversion of pixel distances into real-world measurements. Ultimately, the study calculates the deviations between the tips of each blade relative to a reference blade. Experimental results substantiate the effectiveness and accuracy of the proposed methodology.

***Index Terms:***blade tracking, rotor tracking, rotor track and balance, vertical vibrations in Helicopters

# 2 Introduction

## 2.1 Background

Helicopters are widely used in modern aviation for their ability to hover and perform vertical takeoffs and landings. However, helicopter rides are often uncomfortable due to the significant levels of vibration they produce. These vibrations can lead to structural issues and even accidents. There are two main types of vibrations in helicopters: vertical and lateral. Vertical vibrations, in particular, are caused by the rotor blades being out of alignment, as illustrated in Figure 1. This type of vibration makes the helicopter bounce up and down during flight. It occurs because one of the blades lifts the helicopter during one part of its rotation but loses lift in the remaining quadrants.

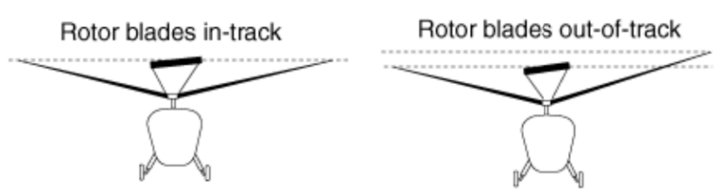


Figure 1: In-track and out of track blades [1]

Blade tracking is a critical process used to manage vertical vibrations. It involves calculating and adjusting the vertical position of each blade’s tip based on its position in the air. Typically, one blade is selected as a reference, and the position of the other blades’ tips is measured relative to this reference blade. If the difference in blade tip position falls within a certain threshold (usually around 20 mm), the blades are considered to be in track; otherwise, they are deemed out of track or misaligned. This threshold may vary for different helicopter models. Blade tracking can be performed both in-flight and on the ground.

Various methods have been employed in the past for blade tracking. The oldest method is known as flag tracking, where each blade is painted with a different colored wet paint, and an operator holds a flag near the rotating blade tips. When the blades touch the flag, marks are left on it, and the out-of-track values are determined from these marks. The drawbacks to this method are obvious. It was dangerous, restricted to ground only, and did not allow for track measurements in flight. The use of static rotor balancing devices is not applicable to some aircraft.

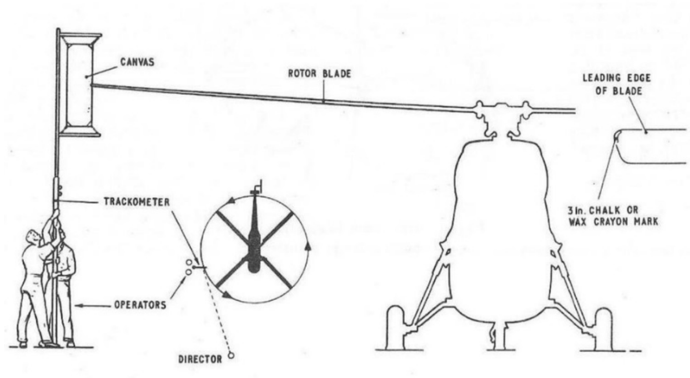


Figure 2: Track Balancing in Helicopters – Evolution in equipment [1]

Over the past few decades, various methods have been explored for blade tracking in helicopters. One approach involved radar systems like the Micropower Impulse Radar (MIR), which offered exceptional accuracy but came with a high cost and complexity.
Vibration sensors mounted at specific locations on the airframe were another avenue of development. While these sensors helped reduce vertical vibrations, they didn't ensure perfect blade alignment.
Several optical methods also emerged for obtaining blade tracking data without attaching targets to the blade tips or visually estimating rotor blade positions from a distance. However, a drawback of these systems was that the influence coefficients used in the software varied from one aircraft to another of the same make and model. All the previously employed techniques had their limitations, and the ones without drawbacks were often expensive.

## 2.2 Motivation

The motivation behind this project is to make helicopter travel safer and more efficient. Helicopter rotor blades play a pivotal role in ensuring the safe operation of these aircraft, and any deviations in their alignment or "out-of-track" conditions can have critical consequences.
Furthermore, ensuring the proper alignment of helicopter blades is essential for optimizing performance and minimizing wear and tear. By automating the tracking and alignment assessment process, this project not only enhances safety but also contributes to the longevity and efficiency of helicopter operations, ultimately benefiting both the aviation industry and the passengers who rely on these aircraft.
In a nutshell, this project is all about improving safety, efficiency, and cost-effectiveness in helicopter travel.

## 2.3 Objectivies

The objectives of this technique include:

1. Reducing vertical vibrations.
2. Designing a system suitable for indoor/outdoor use and in-flight/on-ground operation.
3. Developing a system that requires no modifications to the blades like attaching sensors to blade tips.
4. Creating an affordable system.

This approach utilizes image processing techniques and is divided into several steps, including image filtering, image thresholding, precise determination of each blade's position, and conversion of pixel distances into real-world measurements. This method aims to provide accurate results while overcoming the drawbacks associated with previous techniques.

# 3 Literature Review

## 3.1 Rotor Track and Balance (RTB) Techniques (Bechhoefer et al [2])

The study introduced the idea of rotor blade adjustments using weights (WTS), pitch control rods (PCR), and trailing edge tabs (TAB) to balance out inherent blade non-uniformities. Additionally, Ferrer (2001) laid the groundwork for later algorithmic developments in RTB by highlighting the linearity of adjustment coefficients. Multiple equivalent solutions are produced when the Fourier transform is applied to the time domain, necessitating the development of a method to determine actual blade adjustments. Initially, all efforts to reduce blade non-uniformity began with a desire to reduce track split errors. Since rotor track and balance's main objective is to reduce vibration, finding an effective solution to the issue is a driving force.

## 3.2 Use of the Hough Transformation To Detect Lines and Curves in Pictures (Duda et al) [4]

Richard O. Duda's paper introduces the idea of transforming figure points into a parameter space to identify concurrent lines, a technique first proposed by Hough. Each figure point is transformed into a straight line in a parameter space defined by parametric representations of lines in the picture plane. A key foundation is the concept of representing lines in a parameter space, particularly using a normal parameterization. Straight lines are parametrically represented using normal parameters, specifically the angle $(\theta)$ of the normal and its algebraic distance $(\rho)$ from the origin. This representation leads to the equation of a xy-plane line. By restricting $\theta$ to the interval [0, $\pi$], each line in the xy-plane corresponds to a unique point in the $\theta - \rho$ plane.
Properties of Point-to-Curve Transformation:

> **Property 1:** A point in the picture plane corresponds to a sinusoidal curve in the parameter plane.
>
> **Property 2:** Designing a system suitable for indoor/outdoor use and in-flight/on-ground operation.

**Property 3:** Developing a system that requires no modifications to the blades like attaching sensors to blade tips.

**Property 4:** Creating an affordable system.

The properties are used to solve the problem of finding colinear points in a picture plane. The problem of finding colinear points is transformed into the problem of finding concurrent curves by transforming figure points into sinusoidal curves in the parameter plane. This method provides computational advantages when detecting colinear or nearly colinear figure points.

## 3.3 A Novel Shi-Tomasi Corner Detection Algorithm Based on Progressive Probabilistic Hough Transform (Mu et al) [6]

The Moravec algorithm is the foundation of Shi-Tomasi. The concept of Moravec corner detection is as follows: Make a detection window in the image. By moving the window slightly in all directions, the average power of the window is determined. When the energy change value exceeds the threshold value, the central pixel of the window is extracted as a corner point. Assuming that the gradation of the point (x, y) is f(x, y) f(x,y), suppose each pixel point (x, y) in the image is moved separately with the distance of (u, v), the gradation of pixel point can be represented by: This method can only detect the intensity change of the

$$\boxed{E_{u,v}(x, y) = \sum_{u,v} \omega_{u,v} [f(x + u, y + v) - f(x, y)]^2}$$

window function moving in 8 basic directions, so the Moravec operator lacks rotation invariance. This means that if the target image is rotated by 15 degrees, the original detected corner point cannot be detected, and the point that was not the corner point may become a corner point, causing the method to fail to extract the stable corner point accurately. As a result, Shi-Tomasi algorithm detects corner points using differential operation and autocorrelation matrix. This paper also discusses the Hough transform, which is one of the fundamental methods for recognizing geometric shapes from images in image processing.

### 3.3.1 Shi-Tomasi corner detection based on PPHT:

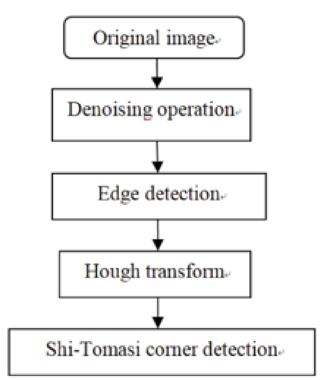


Figure 3: Algorithm flowchart

The basic intuition is that corners can be detected by looking for significant changes in all directions. We consider a small window on the image and then scan the whole image, looking for corners. Shifting this small window in any direction will result in a large change in appearance if that particular window happens to be located on a corner.

1. Flat regions will have no change in any direction.

2. If there's an edge, then there will be no major change along the edge direction.

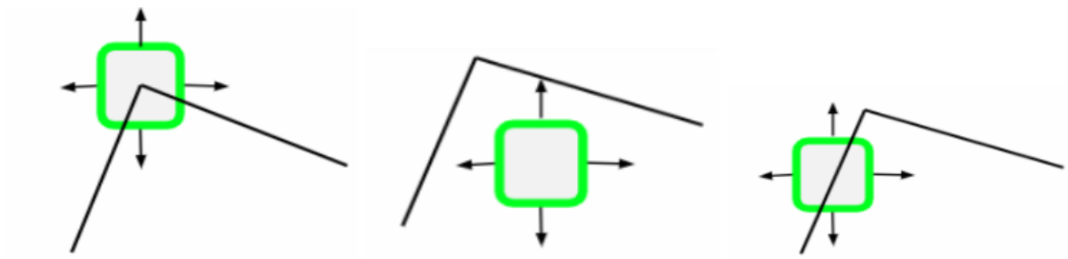

Figure 4: Algorithm flowchart

If we're scanning the image with a window just as we would with a kernel and we notice that there is an area where there's a major change no matter in what direction we actually scan, then we have a good intuition that there's probably a corner there.

### 3.4 New methods for rotor tracking and balance tuning and defect detection applied to Eurcopter products [5]

M. J. Renzi and Ensign's groundbreaking research on rotor track and balancing techniques has significantly advanced our comprehension of optimizing helicopter rotor systems. They underscored the vital importance of minimizing vibrations along the three aircraft axes to ensure the comfort of both crew and passengers during all stages of construction and maintenance. Their study delved into the potential for non-linear adjustments, depending on available data, while staying rooted in fundamental principles such as isotropy and linearity. A remarkable innovation introduced by them was the incorporation of neural networks, simplifying the adjustment process by utilizing acceleration measurements instead of blade monitoring. The software they developed, leveraging these neural networks, efficiently processed acceleration data, resulting in adjustments that closely adhered to manufacturer standards. The practical validation of their methodology through experiments on a 10T helicopter demonstrated its remarkable ability to reduce fuselage vibrations.

### 3.5 Micropower impulse radar [1]

Azevedo, S, and McEwan, T E, created a special radar called micropower impulse radar (MIR) at Lawrence Livermore National Laboratory. Unlike regular radar, MIR is both very sensitive and doesn't use much power. It can send and receive lots of tiny energy pulses super quickly, helping it detect things far away really well. MIR's beginnings can be traced back to the lab's Laser Directorate, showing how smart ideas evolve there. The radar has many uses. It's great for security because it can spot threats efficiently and is affordable. In emergencies, like search and rescue missions, MIR helps find people in trouble. It's also handy for checking the safety of things without causing damage and for various transportation needs. In short, Azevedo and McEwan's MIR radar is a game-changer. It's super sensitive, energy-efficient, and has applications in security, emergencies, safety checks, and transportation."

### 3.6 Using Personal Computer For Vibration Measurements And Rotor Balancing [5]

Tariq Ahmedhamdi, Roshen & Al Jubori, Ayad & Ibrahem, Waleed conducted research in the field of vibration analysis and rotor balancing, addressing the critical issue of vibrational problems commonly associated with prime movers and rotating machinery. These issues arise from inherent unbalance in engines, which can result from design flaws or manufacturing imperfections. Such vibrations not only impact the machinery itself but also affect the supporting structures, potentially leading to material fatigue due to cyclic stress variations. In essence, the objective of their work is to design and implement an advanced computerized system capable of balancing rotating machinery effectively. This system not only identifies the specific blade causing unbalance but also calculates the precise weight adjustments required for rotor balance. Their innovative approach relies on angular position data, offering a promising solution to address machinery vibration challenges and enhance overall operational efficiency. To address these challenges, the researchers embarked on the creation of a computerized system. This system is designed to analyze rotor speeds and vibration levels, pinpointing the exact unbalanced blade. Moreover, it has the capability to calculate the necessary weight adjustments to rectify the imbalance and reduce vibrations. Their research falls within the broader field of vibration analysis, with a particular focus on balancing problems. Unbalanced components such as propellers, rotors, or driveshafts can induce vibrations and stress in rotating parts and their supporting structures. This can impact various aspects, including ride quality, vibration reduction, noise reduction, structural stress reduction, and alleviation of operator fatigue. The ultimate objective of their balancing efforts also encompasses extending the lifespan of bearings, underscoring the relevance of their work across multiple industries.

### 3.7 Longitudinal tip-path-plane measurement using an optics-based system [7]

Sickenberger, Richard & Schmitz, Fredric conducted a noteworthy study in the summer of 2006 that introduced an optics-based tip-path plane measurement system for helicopters. This system, implemented on a Bell 206 helicopter, consists of two cameras measuring the longitudinal tip-path plane angle in relation to the fuselage, along with an air data boom equipped with a horizontal wind vane to measure free-stream velocity concerning the fuselage. To ensure accuracy and reliability, the researchers also integrated a global positioning system and inertial mass unit for comparative purposes. These measurements aimed to assess the imaging system's performance against theoretical tip-path plane values, considering factors like drag-to-weight ratio, flight path angle, and acceleration. The results of this study were highly promising. The tip-path plane angle measurements closely aligned with theoretical predictions and demonstrated exceptional repeatability during steady-state flight maneuvers. Statistical analysis revealed that the standard deviation for the tip-path plane angle relative to the fuselage was just 0.19°, while the standard deviation for the free-stream velocity angle relative to the fuselage was 1.38°. When combined, these measurements yielded a longitudinal tip-path plane angle with a standard deviation of 1.35°. Notably, the study confirmed fundamental principles, showing that the longitudinal tip-path plane angle varies linearly with the square of the velocity and is influenced by the sum of flight path angle and acceleration. These findings are of paramount importance to the field of aviation and helicopter dynamics. In conclusion, Sickenberger, Richard & Schmitz, Fredric's research presented an optics-based measurement system that showcased excellent accuracy and repeatability in assessing the longitudinal tip-path plane angle for helicopters. Their work not only validated theoretical predictions but also reinforced fundamental principles governing helicopter flight dynamics.

## 3.8 Camera Calibration (Open-cv documentation ) [3]

For effective use of a camera as a visual sensor, particularly for precise image analysis and 3D reconstruction, camera calibration is a crucial process. This complex procedure is based on precisely determining both internal and external camera parameters. These parameters include lens distortions, intrinsic aspects such as focal length and optical centres, and extrinsic aspects such as the camera's orientation and position relative to a defined world coordinate system.

### 3.8.1 Parameters:

1. **Distortion:** Cameras introduce distortion due to lens imperfections. The two main types are radial distortion (straight lines appear curved) and tangential distortion (image appears skewed). These distortions can significantly affect image analysis and 3D reconstruction accuracy.

2. **Intrinsic Parameters:** Intrinsic parameters are camera specific properties, including focal length (fx, fy) and optical centres (cx, cy). They form the camera matrix and help correct distortions. A common representation is the pinhole camera model.

3. **Extrinsic Parameters:** Extrinsic parameters involve rotation and translation vectors that position the camera's coordinate system relative to a world coordinate system. These parameters are crucial for 3D scene reconstruction.

4. **Calibration Pattern:** A known pattern (e.g., chessboard) is placed in front of the camera. The pattern's 3D coordinates, and corresponding 2D image coordinates are used to calibrate the camera.

5. **Re-projection Error:** After calibration, re-projected image points are compared with detected image points. Lower re-projection error indicates more accurate calibration.

### 3.8.2 Mathematical Formulations:

1. **Radial Distortion:** Radial distortion is approximated using a polynomial expression:

$$x_{distorted} = x(1 + k_1r^2 + k_2r^4 + k_3r^6)$$
$$y_{distorted} = y(1 + k_1r^2 + k_2r^4 + k_3r^6)$$

2. **Tangential Distortion:** Tangential distortion is caused by lens misalignment:

$$x_{distorted} = x + [2p_1xy + p_2(r^2 + 2x^2)]$$
$$y_{distorted} = y + [p_1(r^2 + 2y^2) + 2p_2xy]$$

2. **Camera Matrix:** The camera matrix combines intrinsic parameters and maps 3D points to 2D image coordinates:

$$Distortion\ coefficients = (k_1 \quad k_2 \quad p_1 \quad p_2 \quad k_3)$$

$$camera\ matrix = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix}$$

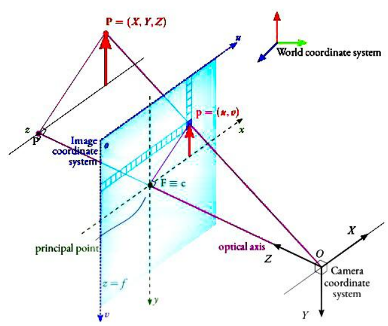


Figure 5: Camera Pinhole model

# 4 Experimental Setup

Subsequently, for the purpose of track checking, we created a tabletop dummy helicopter. This involved integrating a 12v DC motor with an aluminum shaft, to which adjustable blades were affixed. These blades could be modified to suit various experimental setups. Additionally, we incorporated a motor driver into the model to regulate its speed. We recorded video of our this model from different angle.

Table 1: Errors in Verticle distance of Blades

| Experiment ($mm$) | Number of baldes ($mm$) | distance between blades ($mm$) |
|---|---|---|
| solidwork 14mm | 3 | 14mm |
| solidwork 9mm | 3 | 9mm |
| dummy model 13mm | 4 | 13mm |
| dummy model 6mm | 4 | 6mm |

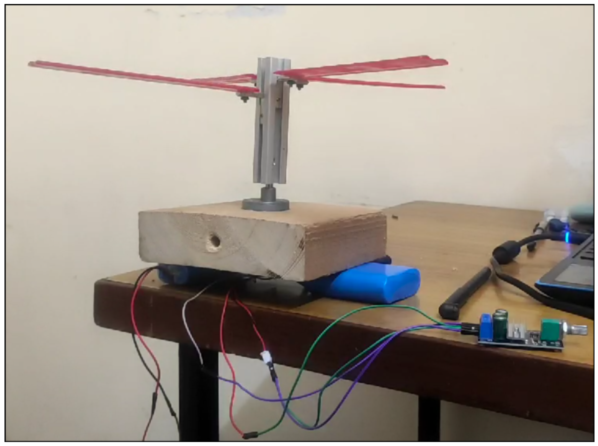

Figure 6: Helicopter dummy model

To ensure accuracy, specific models using SolidWorks were created, effectively minimizing vibrations and reducing noise levels in input data. To ensure accuracy, specific models using SolidWorks were created. Video at same angle to dummy model were stimulated. This allowed us to obtain precise results during our testing.

# 5 Methodology

The proposed work has been implemented using computer vision and it has been divided in various steps.

## 5.1 Data Collection

Numerous videos were recorded to capture moving ceiling fans, at multiple speeds and varying camera settings. In addition to these, some clips of dynamic footage featuring moving cars were also collected.

## 5.2 Camera Calibration

We use a camera calibration as a visual sensor to measure the displacement effectively. Camera calibration is the process of determining these camera parameters such as focal length, optical centre, and radial distortion coefficients of the camera lens, as well as external elements like the camera's rotation and translation concerning a real-world coordinate system. The process of camera calibration involves using chessboard images captured from different angles and positions. OpenCV's functions are employed to detect the corners of the chessboard within the images. These detected corners are then used to calculate crucial parameters, including the camera matrix, distortion coefficients, rotation vectors, and translation vectors.

## 5.3 FMO Detection and Tracking

Subsequently, a program is developed to detect fast-moving objects using image processing. The input videos are loaded into the program and it effectively tracks the motion of the objects, ultimately providing us with accurate measurements of their RPM or speed. The

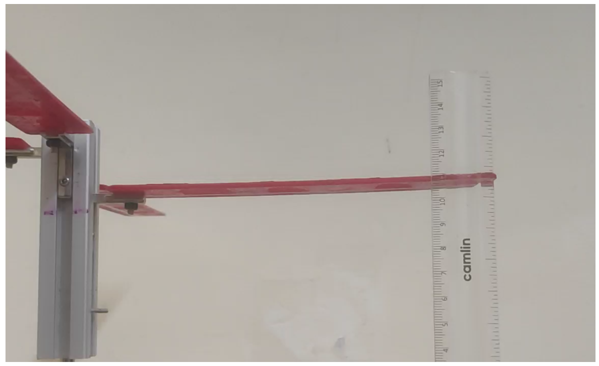


Figure 7: Measuring vertical distance

maximum speed which can be achieved by our program is 370 revolutions per minute (RPM) and hence a frequency of 6.16 Hz. The typical speed of rotation of helicopter's main rotor is almost 350-400 RPM (frequency of 5.83-6.66 Hz).

## 5.4 Color Detection and Masking

Blade tip detection and vertical tracking can often be achieved through traditional computer vision techniques and algorithms. An experimental investigation was carried out to determine the rotational speed, quantified as revolutions per minute (RPM), of a swiftly rotating fan. In order to facilitate this measurement, a distinctive red marker was applied to one of the fan blades. A Python model was developed to analyse video footage capturing the fan's movement. This model not only scrutinize the video content but also accurately tracks the complete rotations executed by the fan, thereby enabling precise RPM calculation. It should be noted that this Python script can be applied to get the RPM of various rotating objects.

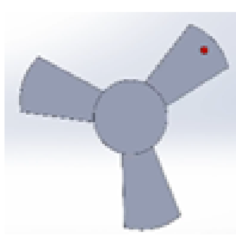

Figure 8: (a) SolidWorks fan with a red mark (b) Red mark on the real fan

When working with helicopter films or photographs, employing specialized image manipulation techniques can be highly advantageous. By employing techniques such as edge detection and contour detection, one can accurately determine the location of helicopter blades and monitor Another effective technique is thresholding, which aids in distinguishing the helicopter blades from the backdrop, particularly when the background exhibits uniformity. By employing these techniques, you can enhance your ability to locate and monitor helicopter blades in films and images.

Figure 9: Edges of blade

## 5.5 Edge Detection

Applied Canny edge detection algorithms to detect the edges of the helicopter blades. Once you have the edges, you can find the blade tip by identifying the highest point along the detected edges. Contour Analysis: Utilized contour analysis to find the blade's contour, and then calculate the center or tip of the contour. This can work well for well-defined blade shapes.

## 5.6 Corner Detection

The corners of an image are basically identified as the regions in which there are variations in large intensity of the gradient in all possible dimensions and directions. Corners extracted can be a part of the image features, which can be matched with features of other images, and can be used to extract accurate information. We have used the Shi-Tomasi corner detection algorithm to identify corners within the frames of our videos. This enabled us to locate key points of interest that can be pivotal for various applications, such as feature matching, tracking, and precise tip coordinates.

Figure 10: Blade corners

## 5.7 Blade Tip Pixel Coordinates

In 2D plane, helicopter rotor blades appeared horizontally aligned. The tip of each blade is the endpoint of the straight lines in the image. X-coordinates (horizontal position) of the tip of each blade were measured, which helps to calculate how far each blade tip went. This step allowed us to know the pixel coordinates of all blades. All the corner point coordinates were stored in a list. We are interested only in the extreme coordinates. The difference in corresponding values of Y coordinates gives the track. These pixel coordinates need to be back-calibrated to real-world units like millimeters, using camera calibration.

## 5.8 Smoothing the Curve

After recording all the x and y coordinates, we needed the y coordinate of each blade corresponding to its extreme position. To achieve this, we sought all local maxima of the x

coordinate and performed curve smoothing using Fourier transform.
Fourier transform shifts the graph from the time domain to the frequency domain. We then

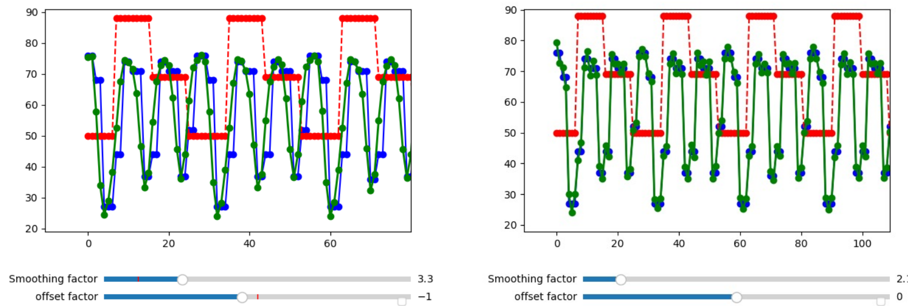


Figure 11: Raw x and y coordinates

filtered out high frequencies to reduce noise in our data. Taking the inverse Fourier transform of the remaining data brought it back to the time domain, resulting in a smooth curve. A slider in the code block allowed users to choose the degree of smoothness, and an offset slider ensured that the maxima coincided despite any displacement caused by smoothing.

## 5.9 Clustering Data Points

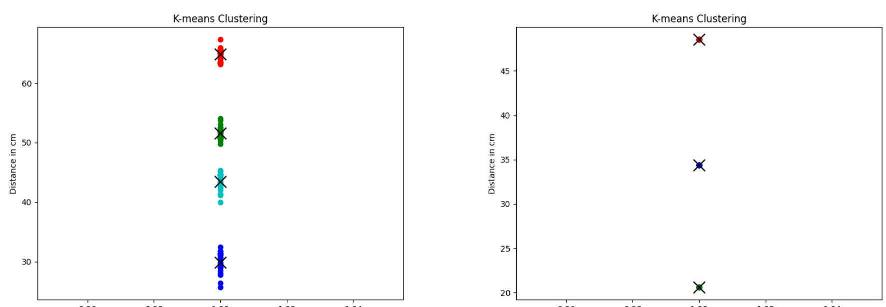


Figure 12: Clustered vertical distances

From all the y coordinates obtained, we aimed to make a meaningful interpretation by clustering the data points. We employed a k-means algorithm for this purpose. The k-means algorithm is centroid-based, associating each cluster with a centroid. Its primary goal is to minimize the sum of distances between data points and their corresponding clusters. This algorithm performs two main tasks:

1. Determines the best value for K center points or centroids through an iterative process.

2. Assigns each data point to its closest k-center, creating clusters based on proximity.

As a result, each cluster comprises data points with commonalities, distinct from other clusters.

# 6 Workflow

The process begins by inputting a known distance into the program, which serves as a reference for subsequent measurements. Lines are then drawn to identify the pixels contained within this known distance, allowing for the determination of a scaling factor. This step ensures accurate spatial representation in the subsequent analysis.
Following this, a region of interest (ROI) is selected, focusing on the specific area containing the helicopter blades. To enhance the quality of the video sample and eliminate unwanted noise, contrast, brightness adjustments, as well as median and Gaussian blurs, are applied.
Within this refined ROI, the goal is to narrow down the data by identifying the range of movement of blade corners. This reduction in data volume simplifies subsequent processing and storage requirements, optimizing the efficiency of the analysis.
Next, the contours of the blades within the ROI are traced, and the x and y coordinates of these blades are recorded in a list. Using this list, a graphical representation is generated to visually depict the movement patterns of the blades. However, due to inherent noise in the data, a Fourier transform is applied to smoothen the curve, providing a clearer representation of blade movement.
To further enhance the precision of displacement predictions, a clustering algorithm is applied specifically to the y coordinates. This step categorizes similar displacement patterns, refining the analysis and providing a more accurate understanding of the helicopter blade movement within the selected region of interest. Overall, these steps collectively contribute to a comprehensive and refined analysis of the video data, extracting valuable insights into the dynamics of the helicopter blades.

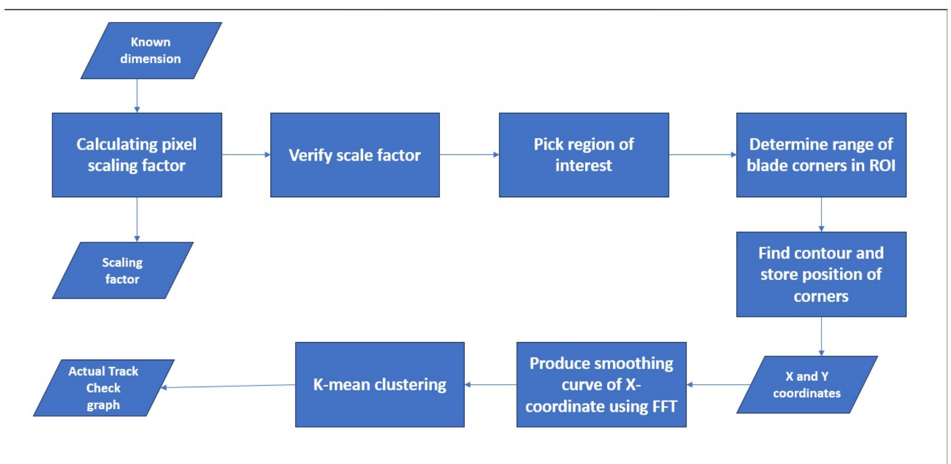


Figure 13: Workflow

# 7 Results and Discussion

Table 2: Verticle distance of Blades results

| Experiment | Actual Displacement $(mm)$ | Predictated Displacement $(mm)$ |
|---|---|---|
| solidwork 14mm | 0 | 0 |
| - | 14 | 13.74 |
| - | 28 | 27.94 |
| solidwork 9mm | 0 | 0 |
| - | 9 | 9.08 |
| - | 18 | 18.16 |
| dummy model 13mm | 0 | 0 |
| - | 13 | 13.58 |
| - | 26 | 21.73 |
| - | 39 | 34.96 |
| dummy model 6mm | 0 | 0 |
| - | 6 | 6.58 |
| - | 12 | 13.76 |
| - | 18 | 19.99 |

The first column serves as a descriptor for our testing videos, with the detailed video descriptions already outlined in the table 1 within the data collection section. The corresponding second and third columns provide a comprehensive overview of the actual and predicted displacements, respectively. The organized format of this presentation streamlines the ability to reference specific video details alongside their corresponding displacement outcomes. This structure significantly aids in achieving a comprehensive understanding of the analysis results, allowing for efficient interpretation and evaluation of the data. Table 3 shows our error estimation in our experiments

Table 3: Errors in Verticle distance of Blades

| Experiment $(mm)$ | Maximum Error $(mm)$ |
|---|---|
| solidwork 14mm | 1.85 % |
| solidwork 9mm | 1.836 % |
| dummy model 13mm | 32.82 % |
| dummy model 6mm | 33 % |

From all the experiments conducted, it is evident that the obtained results are reliable, with a maximum error of 30 %. Notably, when the testing videos are clean and well-aligned, such as in the case of Solidworks 14mm and Solidworks 9mm videos where the blades are directly in front of the camera, the maximum error is a mere 0.25mm, reflecting high accuracy. However, in instances where the videos are not well recorded, the error can increase significantly, reaching up to 4.2mm.

It's essential to acknowledge that video angle and frame rate per second (fps) also play crucial roles in result accuracy. Higher fps values contribute to the generation of smoother curves, enhancing the precision of the results. Therefore, considering video quality and recording conditions is vital for obtaining the most accurate and reliable displacement outcomes.

The primary source of error can be attributed to the limitations of the camera. In our program, we identify extreme points and calculate their corresponding vertical distances. However, the low sample rate, constrained by a low frames per second (fps) setting, might lead to some extreme points escaping detection. Additionally, the imprecision in camera calibration, stemming from poor video quality, contributes to the overall error.

To mitigate these challenges, further optimizations in the program, coupled with the use of higher-quality video recordings, could enhance the precision of the results. A more refined calibration process and improvements in video recording conditions would likely contribute to more accurate and reliable displacement outcomes in future analyses.

## 7.1 Further works

While the current model exhibits certain limitations, there are opportunities for further improvement in subsequent iterations. Notably, the manual camera calibration process, involving mouse and human interaction, can be replaced with an automated procedure. Additionally, the model's susceptibility to video vibrations, not representative of real-life scenarios, calls for advanced techniques to enhance its robustness.

## 7.2 Other application

Certainly, the versatility of this program extends its usability to various applications beyond helicopter blade analysis. The capability to monitor machinery vibrations makes it valuable for predicting the lifespan of equipment. By adapting the program, it can be employed in industrial settings to assess the health and performance of machinery, enabling proactive maintenance and minimizing unexpected breakdowns.

Moreover, with suitable optimizations, the program can find application in construction sites for capturing vibrations in large infrastructure projects. This could be particularly useful in assessing the structural integrity of buildings, bridges, or other constructions. The program's adaptability showcases its potential as a versatile tool with implications for predictive maintenance and structural health monitoring across diverse fields.

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