Track check in Helicopter Main Rotor Blade using Image processing

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List of Abbreviations

RTB	Rotor Track and Balance
WTS	weights
PCR	pitch control rods
TBR	tailing edge tabs

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1. Introduction

1.1 Background

Helicopters are widely used in modern aircraft for their ability to hover and perform vertical take-offs and landings. However, helicopter rides are often uncomfortable due to the significant levels of vibrations they produce. These vibrations can lead to structural issues and even accidents. There are two main types of vibrations in helicopters: [1] vertical vibration and lateral vibration. Vertical vibration is typically due to the rotor blades being out of track as shown in Fig. 1. Due to vertical vibration the helicopter bounces up and down. This vibration is produced by one of the blades lifting the helicopter in one quadrant of rotation and suddenly losing lift in the remaining quadrants [1].

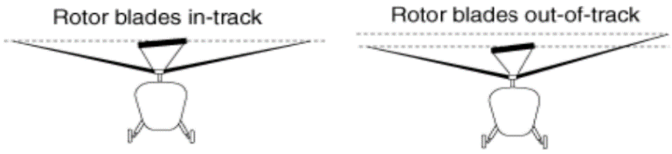


Figure 1. In-track and out of track blades

Blade tracking [2] 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. [1] Blade tracking can be performed both in-flight and on the ground. Various methods have been employed in the past for blade tracking, such as flag tracking, electro-optical tracking, line-scan video camera systems, and radar systems like the Micropower Impulse Radar (MIR). The oldest method is known as flag tracking, where each blade is painted with a different coloured 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.

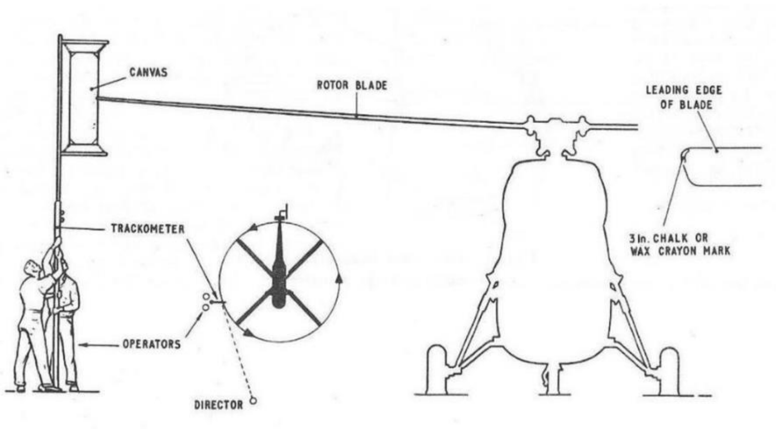


Figure 2. Track Balancing in Helicopters – Evolution in equipment

(51) TRACKING BALANCING HELICOPTERS part 2 | LinkedIn

However, these systems were not appreciated because they typically required alterations to the blades. Introduction of blade alignment techniques based on vibration sensors, which reduced vibrations but did not produce perfect alignment. Due to different coefficients in software programs across airplanes of the same make and type, optical approaches developed but encountered difficulties. All the techniques used in the past had some drawbacks and those which have no drawbacks are very expensive.

1.2 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.

1.3 Objectives

The objectives of this project include:

1. Measure vertical vibrations of blade.
2. Develop a non-contact-based system that is safe, reliable, and requires no modifications to the blades like attaching sensors to blade tips.
3. Explore the possibility of **real-time monitoring** of rotor blade tracks and vibrations during helicopter assembly. This can provide immediate feedback to technicians and allow for adjustments as needed.
4. Minimize human error and increase efficiency by reducing the time required to check rotor blade track and vibrations compared to manual methods.
5. The project aligns with the Indian Air Force and defense military to ensure the immediate requirements and contribute to the safety and reliability of helicopters in their fleet.

2. Literature Review

2.1 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.

2.2 Use of the Hough Transformation To Detect Lines and Curves in Pictures (Duda et al [3])

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 (θ) of the normal and its algebraic distance (ρ) from the origin. This representation leads to the equation of a xy-plane line.
By restricting θ to the interval $[0, \pi)$, each line in the xy-plane corresponds to a unique point in the θ-ρ plane.
Properties of Point-to-Curve Transformation:

1. **Property 1**: A point in the picture plane corresponds to a sinusoidal curve in the parameter plane.
2. **Property 2**: A point in the parameter plane corresponds to a straight line in the picture plane.
3. **Property 3**: Points lying on the same straight line in the picture plane correspond to curves through a common point in the parameter plane.
4. **Property 4**: Points lying on the same curve in the parameter plane correspond to lines through the same point in the picture plane.

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.

2.3 A Novel Shi-Tomasi Corner Detection Algorithm Based on Progressive Probabilistic Hough Transform (Mu et al [4])

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 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 $f(x, y)$ 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:

$$E_{u,v}(x, y) = \sum_{u,v} \omega_{u,v} [f(x + u, y + v) - f(x, y)]^2 \qquad (1)$$

This method can only detect the intensity change of the 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 recognising geometric shapes from images in image processing.

Shi-Tomasi corner detection based on PPHT:

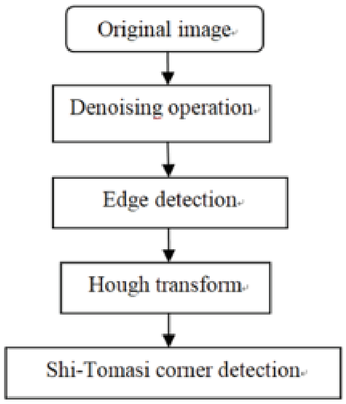


Figure 3 Algorithm flowchart

The algorithm is made up of the following components: First, the necessary preprocessing on the source image is performed, which includes denoising, edge detection, conversion, and grayscale image. The image is then subjected to the Hough line transformation, with the result marked on the image. Finally, the Shi-Tomasi operator is used to detect corners. Hough transform and Shi-Tomasi are two crucial steps in the algorithm. These two steps have a direct impact on the effect of the final corner detection.

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. Fig. 4(a)

1) Flat regions will have no change in any direction. Fig. 4(b)
2) If there's an edge, then there will be no major change along the edge direction. Fig. 4(c)

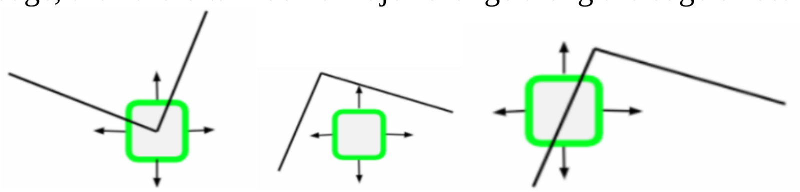


Fig. 4(a) Fig. 4(b) Fig. 4(c)

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.

2.4 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.

2.5 Micropower impulse radar [6]

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.

2.6 Using Personal Computer For Vibration Measurements And Rotor Balancing [7]

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.

2.7 Longitudinal tip-path-plane measurement using an optics-based system [8]

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 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.

2.8 Camera Calibration (OpenCV documentation [9])

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.

2.8.1 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 (f_x, f_y) and optical centre (c_x, c_y). 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.

2.8.2 Mathematical Formulations:

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

$$x_{distorted} = x(1 + k_1r^2 + k_2r^4 + k_3r^6) \qquad (2)$$
$$y_{distorted} = y(1 + k_1r^2 + k_2r^4 + k_3r^6) \qquad (3)$$

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

$$x_{distorted} = x + [(2p_1xy + p_{2(}r^2 + 2x^2)] \qquad (4)$$
$$y_{distorted} = y + [(2p_2xy + p_{1(}r^2 + 2y^2)] \qquad (5)$$

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

$$Distortion\ coefficients = (k_1 \quad k_2 \quad p_1 \quad p_2 \quad k_3) \qquad (6)$$

$$camera\ matrix = \begin{bmatrix} f_x & o & c_x \\ 0 & f_y & cy \\ 0 & 0 & 1 \end{bmatrix} \qquad (7)$$

3. Work Plan

This project 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.

3.1 Gantt Chart:

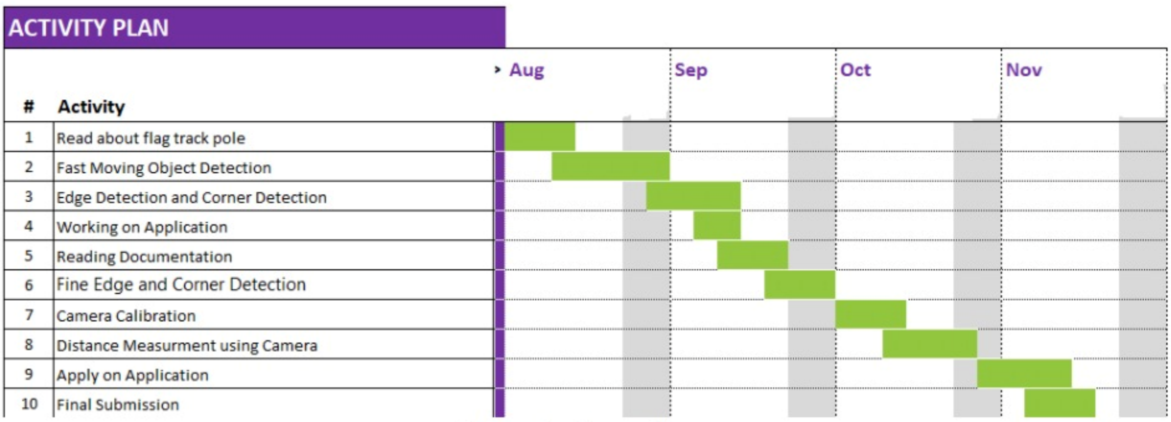


Figure 5. Gantt Chart

4. Work Done

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

4.1 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. To ensure accuracy, specific models using SolidWorks were created, effectively minimizing vibrations and reducing noise levels in input data. This allowed us to obtain precise results during our testing.

4.2 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 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).

4.3 Blade Tip Detection

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 6 (a) SolidWorks fan with a red mark (b) Red mark on the real fan

1. **Image Processing Techniques:** Depending on the quality and characteristics of your helicopter video or images, one can apply image processing techniques such as edge detection, contour detection, and geometric analysis to locate the blade tip and track its vertical position.
2. **Thresholding:** One can use thresholding techniques to isolate the helicopter blades from the background. This can be effective if the background is relatively uniform.

Figure 7 Corner points detection

The program precisely identifies the red marker positioned on the fan blade, tracks its motion, and compute the RPM based on the number of complete rotations captured within the video footage. To utilize this tool, one simply needs to provide the path to the video recording, and it will output the precise RPM value of the rotating object.

4.4 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.

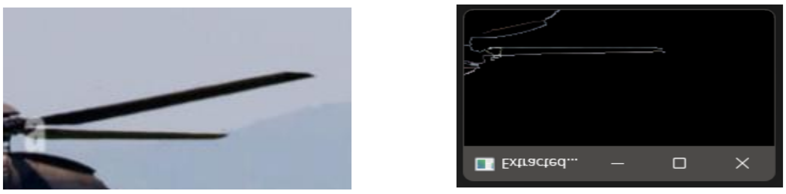


Figure 8 Detected blade images

1. **Contour Analysis**: Utilized contour analysis to find the blade's contour, and then calculate the centre or tip of the contour. This can work well for well-defined blade shapes.
2. **Template Matching:** If the helicopter blades have distinct shapes or patterns, we can use template matching to locate them in the images.
3. **Kalman Filtering:** Implemented Kalman filters or reviewed other tracking algorithms to estimate the vertical position of the blade tip over time. This can help smooth out noisy measurements.

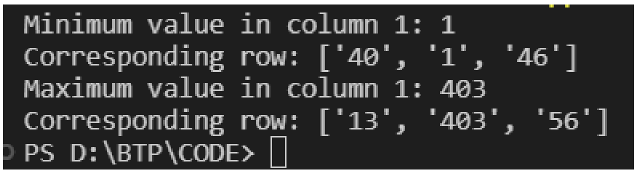
4.5 Corner Detection

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. By extracting these corners with precision and accuracy, we could get the pixel coordinates which can be back calibrated into real coordinates to find the track value.

Figure 9 Detected blade tip

4.6 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 csv file. We are interested only in the extreme coordinates. The difference in corresponding values of Y coordinates gives the track. Though due to negligible changes in few frames, the code may give nearly close values to the leftmost and rightmost X, but their corresponding Y coordinates were almost the same. These pixel coordinates need to be back-calibrated to real-world units like millimetres, using camera calibration.



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Minimum value in column 1: 1
Corresponding row: ['40', '1', '46']
Maximum value in column 1: 403
Corresponding row: ['13', '403', '56']
PS D:\BTP\CODE>
```

Figure 10 Detected extreme coordinates

4.7 Camera Calibration

To use a camera as a visual sensor effectively, it is essential to have a thorough understanding of its characteristics. 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.

The proposed project utilizes computer vision and is organized into two main stages:
In the initial stage, referred to as blade tracking, we recorded videos of the helicopter rotor's blade tips and subjected them to thorough analysis using image processing techniques. The primary aim is to utilize the frames to quantify any misalignment or detect an "out-of-track" condition. The program compared the blade positions within the frames, ultimately determining the extent of misalignment between them in pixel coordinates. In a later stage referred to as the calibration phase, we will create a reference table to establish the relationship between pixels and real-world distances for subsequent stages of the analysis.

5. Future Work

5.1 Camera Calibration

This calibration process is fundamental in achieving reliable and consistent results in our blade tracking system. It ensures that our model can precisely relate the detected blade positions in pixel coordinates to their physical locations in the helicopter's environment.

As of now, we have successfully completed the crucial step of camera calibration, establishing a solid foundation for our helicopter blade tracking system. With the intrinsic and extrinsic camera parameters accurately determined, we will work further on pixel mapping and rigorous testing. Simultaneously, we will test our program's performance on multiple video datasets and other applications like measuring length of any object using camera calibration. This will help in fine-tuning our model's algorithms and parameters, ensuring that it consistently provides accurate and reliable results in practical helicopter operations.

5.2 Model Training and Performance Parameters

The model needs to be tested on a variety of videos captured from different angles and cameras. This diverse training helps our model adapt to various real-world situations, making it robust and versatile. These tests help us evaluate how well our model performs and identify areas that need improvement. By fine-tuning the model's parameters and algorithms based on these tests, we can create an effective model that consistently provides accurate results in different scenarios.

5.3 Field Testing

If circumstances align favourably, we plan to conduct live testing in a defence area where our model will be tested on live video data from helicopters in their natural operational settings. This is a significant step because it allows us to see how well our model performs under real-world conditions, where things can get complex.

During these field tests, we'll assess whether our model is accurate and reliable in practical, sometimes challenging, scenarios. The data we collect in these situations is incredibly valuable. It not only helps us verify the model's functionality but also enables us to make important improvements. We can fine-tune the model's settings and algorithms based on the insights we gain from these tests, ensuring that it can meet the demands of real-world helicopter operations effectively.

5.4 Further Applications

In addition to helicopter blade tracking, we will also be exploring related applications such as analysing the motion of diving boards and tracking vibrations in rulers, etc.

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