REACH TO GRASP MOTION CAPTURING SYSTEM

USING SINGLE CAMERA

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ABSTRACT

Evaluating human motion is crucial for effective physical therapy interventions. This study introduces an innovative system for tracking the motion of the human upper extremity, specifically focusing on functional analysis. Utilizing a single smartphone camera as the core of an optical motion capture system, we captured Reach-to-Grasp (RTG) movements of subjects in a seated position. Image analysis techniques were employed to identify MediaPipe Hand and the Perspective-n-Point (PnP) algorithm located on selected anatomical landmarks of the hand. Through a straightforward camera calibration method, we acquired the 3D coordinates of hand movements. We then calculated two key clinical metrics: grasp aperture and hand transport velocity. These metrics were subsequently compared with data gathered simultaneously from a high-precision Electromagnetic Motion (EM) tracking system. The patterns of results from both systems showed a high degree of correlation. We are currently refining our algorithms based on clinician feedback. This system holds potential for aiding physical therapists in assessing patient movement within clinical environments.

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Sahawatchara Thongprasan

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Introduction

1.1 Background

The assessment of human movement is a critical aspect of physical therapy management. Understanding and analyzing the function of the upper extremity, particularly the Reach-to-Grasp (RTG) movement, is essential for evaluating a patient's motor skills, recovery progress, and the effectiveness of therapeutic interventions. Traditional methods of assessing these movements often involve high-cost equipment, such as Electromagnetic Motion (EM) tracking systems, which may not be readily available in all clinical settings. Furthermore, these systems may require complex setup and calibration processes.

A significant application of Motioncapture is its utilization in the healthcare sector, specifically in physical therapy, where it is employed to monitor, analyze, and evaluate human movement [2-3, 8-13]. The system is designed to capture either the entire body or specific parts during various activities. In the context of this work, our focus is primarily on the functions of the upper extremity, with a particular emphasis on the Reach-to-Grasp movement.

The Reach-to-Grasp (RTG) movement is a commonly performed activity in human upper limb movement [1]. Deficits in this function often necessitate physical therapy and are typically the aftermath of neurological conditions such as stroke and Parkinson’s disease [2, 8-13]. In a clinical setting, physical therapists analyze the RTG movement through observation or clinical tools [2] . To acquire quantitative measures, the use of a motion tracking system is essential [3]. In this research, the Electromagnetic Motion (EM) tracking system, known for its high resolution and ease of use, is the standard instrument [4-7]. This system delivers the 3D coordinates of sensors positioned on anatomical landmarks at the millimeter scale [5]. However, EM's high cost and lack of portability prevent its use in Telemedicine.

Telemedicine is the use of digital technology to provide medical care and consultations remotely. It is crucial for reaching patients in remote or underserved areas, improving access to healthcare, reducing the need for travel, and enabling ongoing management of chronic conditions. However, Electromagnetic Motion (EM) tracking systems are not suitable for telemedicine because they are expensive and not portable. These systems need costly equipment and complicated setups, making them impractical for use outside of specialized clinics. Computer vision technologies, on the other hand, are more affordable and portable. They allow for remote assessment and monitoring of patient movements without the need for bulky and expensive equipment, making them ideal for telemedicine[15,16].

Computer vision in motion capture can use either multi-camera or single-camera setups. Multi-camera systems provide high accuracy and detailed 3D motion data, which is great for complex motion analysis. However, they are expensive, require extensive setup, and are not portable[17], limiting their use in telemedicine. On the other hand, single camera systems are more affordable and portable, making them ideal for remote healthcare. While they may not be as precise as multi-camera systems, their convenience and lower cost are significant benefits. A single smartphone camera is especially useful for telemedicine because it is cheap and widely available[18]. Using MediaPipe, a machine learning framework by Google, a single smartphone camera can effectively detecting and analyze hand movements. MediaPipe Hand can identify hand keypoints and estimate 3D positions, offering a practical and accessible solution for remote patient monitoring.

MediaPipe Hand is a machine learning framework developed by Google[19] that specializes in hand detecting and pose estimation. It is designed to identify 21 3D hand keypoints, which include the positions of individual finger joints, the palm, and the wrist. The framework is capable of handling both single and multiple hands within the same frame. MediaPipe Hands utilizes a two-step process: first, it employs a palm detector model to identify the location of a hand in the image, and then it applies a hand landmark model to estimate the 21 3D keypoints. This technology is

widely used in various applications, from augmented reality to human-computer interaction, and is praised for its accuracy and robustness.

In a single camera setup, such as the one used by MediaPipe Hand, accurately estimating the depth (Z-axis) of fingertips can be challenging. While MediaPipe provides 3D keypoints, the Z-axis information is generally normalized and relative, not an absolute measure of depth. Depth estimation in this context often relies on cues like object size and perspective, along with previously learned data. Although these methods can offer a reasonable approximation of depth, they may not be as precise as specialized depth-sensing cameras or multi-camera configurations. Therefore, for applications requiring critical depth information, additional hardware or techniques are often recommended.

The Perspective-n-Point (PnP) algorithm[20] is a well-established technique used for solving the pose estimation problem, which involves determining the position and orientation of an object—in this case, a finger—relative to a camera. The algorithm takes as input a set of 'n' 2D points in the image plane, which correspond to 'n' 3D points in the world coordinate system. The goal is to find the orientation and translation matrices that describe the pose of the 3D points relative to the camera.

Our research focuses on the pose estimation of the index and thumb finger's tip using an algorithm system that integrates MediaPipe's hand detection with the Perspective-n-Point (PnP) algorithm. The system is not designed for capturing video frames but utilizes Mediapipe to identify specific landmarks on the index finger. For example, in the index finger, we use the tip and first knuckle keypoints from Mediapipe, as well as the center point between these two keypoints, to create the n points for findex finger. These landmarks are then used as input to the PnP algorithm, which estimates the 3D coordinates of the index finger's tip. The estimated coordinates are subsequently used for kinematic parameter calculation. This approach offers a robust and accurate method for 3D pose estimation of the index finger, providing valuable data for further research and clinical applications.

In this endeavor, we collaborated with physical therapists to create a straightforward motion tracking system aimed at capturing upper extremity functions. The system was designed to analyze the RTG movement using a single smartphone camera. The goal of this study was to compare the parameters derived from our proposed system with those from the EM system. Ultimately, our cost-effective and portable system may offer valuable insights for physical therapists to evaluate their clients' movement in a clinical setting.

1.2 Objective

1) To develop and implement a markerless motion tracking system for the Reach-to-Grasp (RTG) movement using a single smartphone camera. The system should be easy to set up and useful for telemedicine applications. This will be achieved using the MediaPipe framework for hand detection and the Perspective-n-Point (PnP) algorithm for pose estimation.

2) To evaluate the performance and accuracy of the single smartphone camera system by comparing its kinematic parameters with those obtained from a standard motion capture system, specifically the Electromagnetic Motion (EM) tracking system. This comparison will help determine the viability of the smartphone-based system as a cost-effective and portable alternative.

1.3 Hypothesis

1) A single smartphone camera that uses MediaPipe and the PnP algorithm can be effectively used to develop a motion tracking system for the Reach-to-Grasp movement. This system will be capable of providing reliable and accurate 3D pose estimations.

2) The results from the single smartphone camera system will be able to compute kinematic parameters, such as aperture and transport velocity, that are comparable to those obtained from a standard motion capture system like the Electromagnetic Motion (EM) tracking system. This suggests that the smartphone-

based system can serve as a practical and accessible tool for telemedicine applications.

1.4 Scope and limitation of study

1) The study is focused on the development and implementation of a motion tracking system using a single smartphone camera. It investigates the potential of this technology in capturing and analyzing the Reach-to-Grasp (RTG) movement, highlighting its ease of setup and portability, making it suitable for telemedicine applications.

2) The research specifically targets the analysis of the Reach-to-Grasp movement in humans. The key kinematic parameters examined in this study are aperture (the distance between the index finger and thumb during the grasp phase) and transport velocity (the speed at which the hand moves towards the object).

3) The study also involves a detailed comparison of the results obtained from the developed smartphone-based system with those from a higher accuracy Electromagnetic Motion (EM) tracking system. This comparison aims to evaluate the performance and accuracy of the smartphone-based system in measuring the specified kinematic parameters.

4) The detection and tracking accuracy of the system are dependent on the performance of the MediaPipe framework. Any limitations or inaccuracies inherent in MediaPipe's hand detection and pose estimation capabilities will directly impact the overall effectiveness of the motion tracking system developed in this study.

CHAPTER 2

THEORY

2.1 Camera calibration

Camera calibration is a fundamental process in the field of 3D computer vision that aims to establish a precise mathematical relationship between the 3D world and its 2D projection onto the image plane of a camera. This relationship is crucial for accurately extracting metric information from 2D images and performing tasks such as 3D reconstruction, object localization, and camera pose estimation.

The camera calibration process involves determining two sets of parameters: intrinsic parameters and extrinsic parameters. Intrinsic parameters characterize the internal geometry and optical properties of the camera, while extrinsic parameters define the position and orientation of the camera with respect to a known world coordinate system.

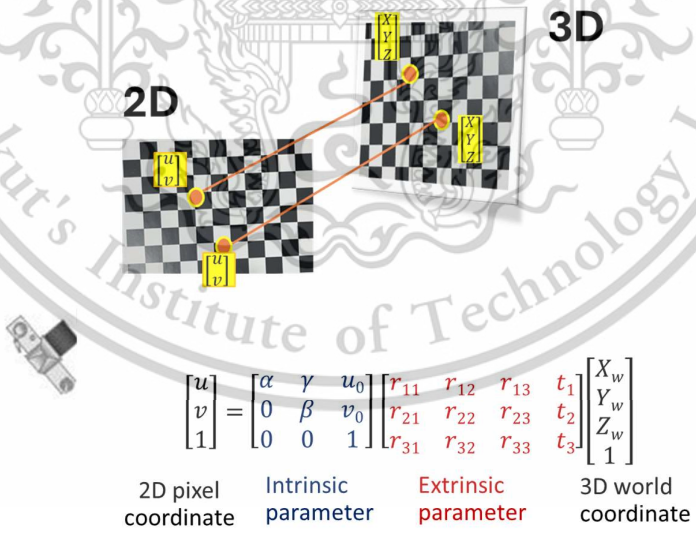

Figure 1 2D to 3D chessboard

The intrinsic parameters of a camera include:

1. Focal Length (f_x, f_y): The distance between the camera's optical center and the image plane, measured in pixels. In an ideal pinhole camera model, f_x and f_y are equal, but they may differ due to non-square pixels.

2. Principal Point (c_x, c_y): The coordinates of the point where the optical axis intersects the image plane. It is usually close to the image center.

3. Skew Coefficient (s): The parameter that represents the skew of the pixel axes. In most modern cameras, the skew is close to zero.

These intrinsic parameters are encapsulated in the camera intrinsic matrix K:

$$K = \begin{bmatrix} f_x & s & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix}$$

The extrinsic parameters of a camera include

The extrinsic parameters consist of a rotation matrix R and a translation vector t, which define the transformation from the world coordinate system to the camera coordinate system. The rotation matrix R is a 3x3 orthogonal matrix, and the translation vector t is a 3x1 vector.The relationship between a 3D point Pw in the world coordinate system and its corresponding 2D projection p on the image plane can be expressed using the perspective projection equation:

$$p = K[R|t]P_w$$

where $[R|t]$ represents the concatenation of the rotation matrix and the translation vector.

Calibration Techniques

There are various techniques for camera calibration, including:

1. Direct Linear Transformation (DLT): This method uses a set of known 3D points and their corresponding 2D projections to estimate the camera matrix $P=K[R|t]$ by solving a system of linear equations.

2. Tsai's Method: This two-stage technique first estimates the extrinsic parameters using a set of 3D-2D point correspondences and then solves for the intrinsic parameters.

3. Zhang's Method: This flexible approach uses multiple views of a planar pattern (e.g., a checkerboard) to estimate both intrinsic and extrinsic parameters. It is widely used in computer vision libraries like OpenCV.

Lens Distortion

In addition to the pinhole camera model, real cameras exhibit lens distortions that affect the mapping between 3D points and their 2D projections. The two main types of distortions are:

1.Radial Distortion: Caused by the curvature of the lens, resulting in the "barrel" or "pincushion" effect. It is modeled using the following equations:

$$x_{distorted} = x(1 + k_1 r^2 + k_2 r^4 + k_3 r^6)$$

$$y_{distorted} = y(1 + k_1 r^2 + k_2 r^4 + k_3 r^6)$$

where (x,y) are the undistorted coordinates, $(x_{distorted},y_{distorted})$ are the distorted coordinates, r is the radial distance from the principal point, and k_1, k_2 , k_3 are the radial distortion coefficients.

2.Tangential Distortion: Caused by the misalignment of the lens and the image plane. It is modeled using the following equations:

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

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

where p_1 and p_2 are the tangential distortion coefficients.

The distortion coefficients are estimated during the calibration process and used to undistort the images before further processing.

Zhang's method is a popular camera calibration method that uses a planar checkerboard pattern (chessboard). The process involves taking several images of this pattern at different orientations and then solving for the camera parameters.

overview of the process:

1. Preparation: Print a chessboard pattern and attach it to a flat surface. Ensure the camera and chessboard are in focus and well lit.

2. Capture Images: Take multiple images of the chessboard pattern from different angles and distances. Make sure to cover as much of the field of view as possible.

3. Identify Corners: For each image, identify the intersection points (corners) of the chessboard. This can be done manually, but there are also many computer vision libraries (like OpenCV) that can do this automatically.

4.Estimate Homography: For each image, estimate the homography that maps the 2D chessboard coordinates to the 2D image coordinates. The homography is a 3x3 matrix that encapsulates the rotation and translation between the chessboard and the camera.

5.Compute Camera Parameters: Using the homographies from step 4, compute the camera's intrinsic and extrinsic parameters. The intrinsic parameters include the focal length and optical centers, and the extrinsic parameters describe the camera's orientation and position in space.

1. Projection from world coordinates to image coordinates with camera intrinsics and extrinsics:

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} \alpha & \gamma & u_0 \\ 0 & \beta & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ 0 \\ 1 \end{bmatrix}$$

2. Simplified form when Z_w=0 with the same numerical values:

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} \alpha & \gamma & u_0 \\ 0 & \beta & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & t_1 \\ r_{21} & r_{22} & t_2 \\ r_{31} & r_{32} & t_3 \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ 1 \end{bmatrix}$$

3. Numerical example of a Homography matrix H:

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = H \begin{bmatrix} X_w \\ Y_w \\ 1 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ 1 \end{bmatrix}$$

4. Homography vectorization:

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} h_1^T \\ h_2^T \\ h_3^T \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ 1 \end{bmatrix}$$

Where $h_i{}^T$ represents the transpose of the i-th row of H, and Pcollects the elements of h_1, h_2, and h_3 within a parameter vector for optimization or other computational purposes.

5. Equations for computing u and v using homography components

$$u = \frac{h_1^T \cdot P}{h_3^T \cdot P}, \quad v = \frac{h_2^T \cdot P}{h_3^T \cdot P}$$

Where h_i^T denotes the transpose of the i-th row of the homography matrix H*H*, and P is the point in homogenous coordinates.

6. Re-arranged equations to express in terms of zero:

$$(h_1^T - u \cdot h_3^T) \cdot P_i = 0, \quad (h_2^T - v \cdot h_3^T) \cdot P_i = 0$$

7. Matrix form of the system for all points:

$$\begin{bmatrix} P_1^T & 0 & -u_1 P_1^T \\ 0 & P_1^T & -v_1 P_1^T \\ \vdots & \vdots & \vdots \\ P_n^T & 0 & -u_n P_n^T \\ 0 & P_n^T & -v_n P_n^T \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \\ h_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix}$$

8.This large matrix equation is typically represented as $A \cdot H$=0, where A is the coefficient matrix constructed from the point correspondences, and H represents the flattened homography matrix.

9.Homography Decomposition:

$$H = \begin{pmatrix} h_0 & h_1 & h_2 \end{pmatrix} = A \cdot \begin{pmatrix} r_0 & r_1 & t \end{pmatrix}$$

$$h_0^T \cdot (A^{-1})^T = r_0^T, \quad h_1^T \cdot (A^{-1})^T = r_1^T$$

As r0 ,r1 form an orthonomal basis

$$\boldsymbol{r}_0^\intercal \cdot \boldsymbol{r}_1 = \boldsymbol{r}_1^\intercal \cdot \boldsymbol{r}_0 = 0$$

$$\boldsymbol{h}_0^\intercal \cdot (\mathbf{A}^{-1})^\intercal \cdot \mathbf{A}^{-1} \cdot \boldsymbol{h}_1 = 0 \quad \boxed{1}$$

$$\boldsymbol{r}_0^\intercal \cdot \boldsymbol{r}_0 = \boldsymbol{r}_1^\intercal \cdot \boldsymbol{r}_1 = 1 \quad \boxed{2}$$

$$\boldsymbol{h}_0^\intercal \cdot (\mathbf{A}^{-1})^\intercal \cdot \mathbf{A}^{-1} \cdot \boldsymbol{h}_0 = \boldsymbol{h}_1^\intercal \cdot (\mathbf{A}^{-1})^\intercal \cdot \mathbf{A}^{-1} \cdot \boldsymbol{h}_1$$

Zhang substitutes the above expression by a new matrix is B

$$\mathbf{B} = \mathbf{A}^{-T}\mathbf{A}^{-1} \equiv \begin{bmatrix} B_{11} & B_{12} & B_{13} \\ B_{12} & B_{22} & B_{23} \\ B_{13} & B_{23} & B_{33} \end{bmatrix}$$

assign $\mathbf{b} = [B_{11}, B_{12}, B_{22}, B_{13}, B_{23}, B_{33}]$

B is symmetry matrix

$$h_0^T \cdot \mathbf{B} \cdot h_1 = 0 \quad [1] \qquad h_0^T \cdot \mathbf{B} \cdot h_0 - h_1^T \cdot \mathbf{B} \cdot h_1 = 0 \quad [2]$$

See pattern in constant

$$h_0^T \cdot \mathbf{B} \cdot h_1 = 0$$
$$h_0^T \cdot \mathbf{B} \cdot h_0 - h_1^T \cdot \mathbf{B} \cdot h_1 = 0$$

$$\mathbf{h}_i^T \mathbf{B} \mathbf{h}_j = \mathbf{v}_{ij}^T \mathbf{b}$$

$$\mathbf{v}_{01}^T \mathbf{b} = 0$$
$$(\mathbf{v}_{00} - \mathbf{v}_{11})^T \mathbf{b} = 0$$

Two constraints, from homography, become

$$\begin{matrix} \mathbf{v}_{01}^T \mathbf{b} = 0 \\ (\mathbf{v}_{00} - \mathbf{v}_{11})^T \mathbf{b} = 0 \end{matrix} \longrightarrow \begin{bmatrix} \mathbf{v}_{01}^T \\ (\mathbf{v}_{00} - \mathbf{v}_{11})^T \end{bmatrix} \mathbf{b} = 0$$

If observed n>=3 images of model plane

image 1 — image n

$$\begin{bmatrix} \mathbf{v}_{01}^T \\ (\mathbf{v}_{00} - \mathbf{v}_{11})^T \\ \cdots \\ \mathbf{v'}_{01}^T \\ (\mathbf{v'}_{00} - \mathbf{v'}_{11})^T \end{bmatrix} \mathbf{b} = 0$$

$$\mathbf{V}\mathbf{b} = 0$$

estimate b with SVD

Equation for vector b representing the elements of matrix B

$$b = \begin{bmatrix} B_{11} & B_{12} & B_{22} & B_{13} & B_{23} & B_{33} \end{bmatrix}$$

Relationship between matrix B and intrinsic camera parameters

We can calculate intrinsic parameter from

$$\mathbf{B} = \mathbf{A}^{-T}\mathbf{A}^{-1}$$

$$\begin{bmatrix} B_{11} & B_{12} & B_{13} \\ B_{12} & B_{22} & B_{23} \\ B_{13} & B_{23} & B_{33} \end{bmatrix} = \begin{bmatrix} \frac{1}{\alpha^2} & -\frac{\gamma}{\alpha^2\beta} & \frac{v_0\gamma - u_0\beta}{\alpha^2\beta} \\ -\frac{\gamma}{\alpha^2\beta} & \frac{\gamma^2}{\alpha^2\beta^2} + \frac{1}{\beta^2} & -\frac{\gamma(v_0\gamma - u_0\beta)}{\alpha^2\beta^2} + \frac{v_0}{\beta^2} \\ \frac{v_0\gamma - u_0\beta}{\alpha^2\beta} & -\frac{\gamma(v_0\gamma - u_0\beta)}{\alpha^2\beta^2} + \frac{v_0}{\beta^2} & \frac{(v_0\gamma - u_0\beta)^2}{\alpha^2\beta^2} + \frac{v_0^2+1}{\beta^2} \end{bmatrix}$$

This matrix B is a representation of the intrinsic parameters of the camera, where:

α is the focal length in terms of pixels in the x-direction

β is the focal length in terms of pixels in the y-direction

γ is the skew coefficient between x and y coordinates

u_0 and v_0 are the coordinates of the principal point of the camera.

Calculation Stepsfor get intrinsic. Define variables w, d, α, β, γ, uc, and vc based on elements of B

$$w \leftarrow B_0B_2B_5 - B_1^2B_5 - B_0B_4^2 + 2B_1B_3B_4 - B_2B_3^2$$

$$d \leftarrow B_0B_2 - B_1^2$$

$$\alpha \leftarrow \sqrt{\frac{w}{d \cdot B_0}}$$

$$\beta \leftarrow \sqrt{\frac{w}{d^2 \cdot B_0}}$$

$$\gamma \leftarrow \frac{w}{d^2 \cdot B_0} \cdot B_1$$

$$u_c \leftarrow \frac{B_1B_4 - B_2B_3}{d}$$

$$v_c \leftarrow \frac{B_1B_3 - B_0B_4}{d}$$

Assemble the Intrinsic Matrix

$$A \leftarrow \begin{bmatrix} \alpha & \gamma & u_c \\ 0 & \beta & v_c \\ 0 & 0 & 1 \end{bmatrix}$$

This sequence of equations effectively extracts the intrinsic camera parameters—focal lengths (α and β), skew (γ), and principal point coordinates (u_c and v_c)—from the matrix B.

Calculating Extrinsic parameter from Homography and Intrinsic parameter

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} \alpha & \gamma & u_0 \\ 0 & \beta & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ Z_w \\ 1 \end{bmatrix}$$

2D pixel coordinate | Intrinsic parameter | Extrinsic parameter | 3D world coordinate

Decomposition of the Homography Matrix:

Given a homography matrix H and intrinsic parameters matrix A, the extrinsic parameters can be calculated as follows:

$$H = [h_1 \quad h_2 \quad h_3] = A[r_1 \quad r_2 \quad t]$$

Calculate Rotation Vectors:

The columns r_1 and r_2 are computed by inverting A and multiplying it with h_1 and h_2 respectively:

$$r_1 = A^{-1}h_1, \quad r_2 = A^{-1}h_2$$

r_3, the third column of the rotation matrix, is calculated as the cross product of r_1 and r_2:

$$r_3 = r_1 \times r_2$$

Calculate Translation Vector:

The translation vector t is calculated by multiplying the inverse of A with h_3:

$$t = A^{-1} h_3$$

Figure 2 chessboard multiple view

2.2 Motion Capture Systems

Motion Capture (MoCap) Systems are technologies designed to monitor and track the movement of objects. These systems can be developed using a variety of technologies, and they are primarily categorized into two types: optical-based and non-optical based systems.

1) Non-optical based MoCap Systems: These systems do not rely on cameras or light to capture motion. Instead, they use other types of detectors to track movement. Examples of non-optical systems include those that use Inertial Measurement Units (IMUs), which capture motion through accelerometers and gyroscopes, and electromagnetic sensors, which track the movement of objects within a magnetic field. This study using electromagnetic for standard

2) Optical-based MoCap Systems: These systems utilize image sensors, such as video cameras, to capture motion. They work by tracking markers or features, which can either be placed on the object (marker-based) or identified through image analysis (markerless). The captured data is then processed to construct a digital representation of the object's movement.

Each type of system has its own advantages and limitations, and the choice between optical and non-optical systems often depends on the specific requirements of the application.

2.3 MediaPipe Hands

MediaPipe Hands, developed by Google, is a specialized machine learning framework for hand tracking and pose estimation. The framework operates through a two-step process for enhanced accuracy and robustness. In Step 1, a palm detection model is employed to scan the input frame and identify the bounding box around the hand or hands present. This model is trained to recognize the unique features and contours of a palm, effectively isolating the hand region from the rest of the image. Once the palm area is detected, Step 2 is initiated. Here, a hand landmark model takes over, focusing on the previously identified bounding box. This model is designed to estimate 21 3D keypoints, which represent anatomical landmarks on the hand, such as the tips and bases of each finger, the palm, and the wrist. These keypoints are then output as 3D coordinates, providing a detailed representation of hand pose. The framework is versatile, capable of handling both single and multiple hands within the same frame, and finds extensive applications in fields like augmented reality, sign language recognition, and human-computer interaction.

Figure 3 Pose estimation by Mediapipe

2.3.1 Architecture

Hand tracking system employs a machine learning (ML) pipeline that integrates two distinct models to enhance tracking accuracy and efficiency:

1. Palm Detector Model: This model processes the entire input image to detect the presence and location of palms. It outputs an oriented hand bounding box

2. Hand Landmark Model: Upon receiving the cropped image of the hand from the palm detector, this model predicts high-fidelity 2.5D hand landmarks.

The integration of these models reduces the necessity for extensive data augmentation techniques such as rotations, translations, and scaling. This is because the hand landmark model receives a well-oriented and scaled input, allowing it to focus primarily on the accuracy of landmark localization. In real-time scenarios, the system optimizes processing by reusing the landmark predictions from the previous frame to define the bounding box for the current frame:

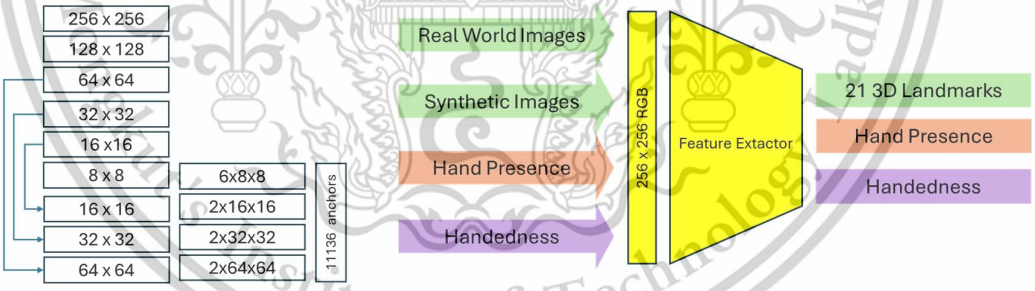

Figure 4 Palm detector model architecture(left). Hand landmark model architecture (right) .

The model has three outputs sharing a feature extractor. Each head is trained by correspondent datasets marked in the same color.

The BlazePalm Detector employs a single-shot detection model, optimized for mobile real-time applications, to identify initial hand locations. This model, inspired by BlazeFace, is designed to tackle the inherent complexities of hand detection, including the wide range of hand sizes, occlusion challenges, and the absence of high-contrast features typical of faces. The approach can be broken down into several key strategies, each contributing to the model's effectiveness:

1. Palm Detection Strategy:

The model focuses on detecting palms rather than the entire hand, simplifying the problem to identifying more rigid objects. This is represented as:

$$B_{\text{palm}} = \text{Detect}(I)$$

where B_{palm} denotes the bounding box of the detected palm and I represents the input image. Palms are detected using square bounding boxes, reducing the complexity and number of anchors needed.

2. Feature Extraction:

An encoder-decoder architecture, akin to a Feature Pyramid Network (FPN), is utilized for feature extraction. This allows for enhanced scene context awareness, crucial for detecting smaller objects like palms within a wide range of scales. The feature extraction process can be mathematically described as:

$$F = \text{ExtractFeatures}(I)$$

where F represents the extracted features from the input image I.

3. Focal Loss Minimization:

To address the challenge of a large number of anchors due to high scale variance, the focal loss is minimized during training. This is crucial for focusing the model's learning on hard-to-detect examples and is represented as:

$$L_{\text{focal}} = -\alpha_t(1-pt)^{\gamma}\log(p_t)$$

where L_{focal} is the focal loss, α_t is the alpha factor, p_t is the predicted probability of the target class, and γ is the focusing parameter.

The Hand Landmark Model operates subsequent to the palm detection phase, focusing on precise localization of hand landmarks within the detected regions. This model is designed to output 21 2.5D coordinates representing hand landmarks, along with additional classifications regarding hand presence and handedness. The mathematical representation of the model's operations can be detailed as follows:

1. Landmark Localization:

The model regresses to 21 hand landmarks, each consisting of x, y, and relative depth coordinates. This can be represented by:

$$\{L_i\}_{i=1}^{21} = \text{Localize}(I_{\text{cropped}})$$

where $\{L_i\}$ denotes the set of 21 landmarks and I_{cropped} is the cropped image of the hand region provided by the palm detector.

2. Hand Presence Flag:

A probability score indicating the presence of a hand in the input image is computed, which can be represented as:

$$P_{\text{hand}} = \text{Probability}(I_{\text{cropped}})$$

where P_{hand} is the probability of hand presence.

3. Handedness Classification:

The model classifies whether the detected hand is left or right, which is crucial for applications requiring differentiated functionalities for each hand. This is represented as:

$$H = \text{ClassifyHandedness}(I_{\text{cropped}})$$

where H indicates the handedness (left or right).

The model's training incorporates both real-world and synthetic datasets to learn the 2D coordinates, while the relative depth is specifically learned from synthetic images. This dual-source training enhances the model's robustness to variations in hand visibility and occlusion.Additionally, to ensure reliability in real-time applications, the model includes a mechanism to trigger a reset in tracking if the hand presence probability falls below a certain threshold. This is crucial for

maintaining continuous and accurate tracking, especially in dynamic environments. The model's architecture is optimized for real-time inference on mobile GPUs, with variations designed to accommodate different computational resources, such as CPUs on mobile devices and more powerful desktop setups.

The dataset and annotation process for the hand tracking system is structured to address various aspects of hand detection and landmark localization through a combination of real-world, in-house, and synthetic datasets:

1. In-the-Wild Dataset:This dataset comprises 6,000 images featuring a broad range of conditions such as geographical diversity, different lighting scenarios, and varied hand appearances. However, it lacks images with complex hand articulations. This dataset primarily supports the palm detector, focusing on hand localization across diverse appearances.

2. In-House Collected Gesture Dataset:Containing 10,000 images, this dataset is designed to cover various angles of all physically possible hand gestures, captured from 30 individuals. The backgrounds in these images are relatively uniform, limiting variability. This dataset complements the in-the-wild dataset by enhancing the robustness of the hand landmark model against different gesture types.

3. Synthetic Dataset:To address gaps in hand pose coverage and depth perception, a synthetic dataset is created using a commercial 3D hand model rigged with 24 bones and 36 blendshapes for detailed finger and palm movements. This model is rendered over various backgrounds, producing 100,000 images from video sequences of transitioning hand poses. Each pose is rendered with random high-dynamic-range lighting and from three different camera angles. This dataset is crucial for training the hand landmark model, especially for depth learning and complex pose recognition.

Annotation Process:

- Real-world images are annotated with 21 hand landmarks. For synthetic images, projected ground-truth 3D joints are used for annotation.
- A subset of real-world images is selected as positive examples for hand presence, while regions excluding annotated hand areas serve as negative examples.
- Handedness is annotated on a subset of real-world images to provide data necessary for distinguishing between left and right hands.

Each dataset plays a specific role in training the models, with the in-the-wild dataset focusing on palm detection due to its high variability and the other datasets enhancing the hand landmark model's accuracy and robustness.

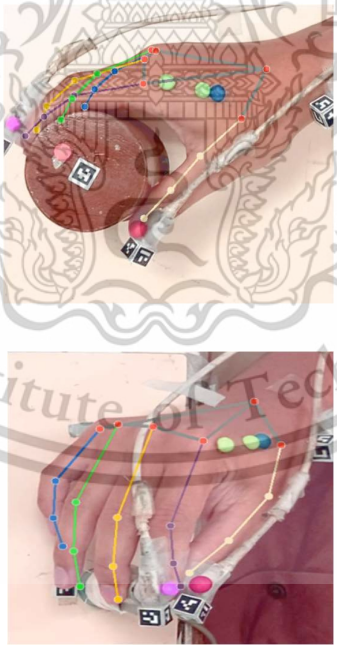

Figure 5 Examples of datasets. (Top): Annotated realworld images. (Bottom): Rendered synthetic hand images with ground truth annotation.

2.3.2 Tracking

After the initial detection of the hand keypoints, the tracking algorithm uses the spatial location of these keypoints from the previous frame to predict their location in the current frame. This prediction serves as a region of interest (ROI) for the palm detection model in the next frame, effectively narrowing down the search area and making the process more efficient. By using the keypoints' spatial information from previous frames, MediaPipe is able to achieve smooth and robust tracking of hand movements across consecutive frames. This tracking algorithm is optimized for real-time performance and is capable of handling rapid hand movements and occlusions.

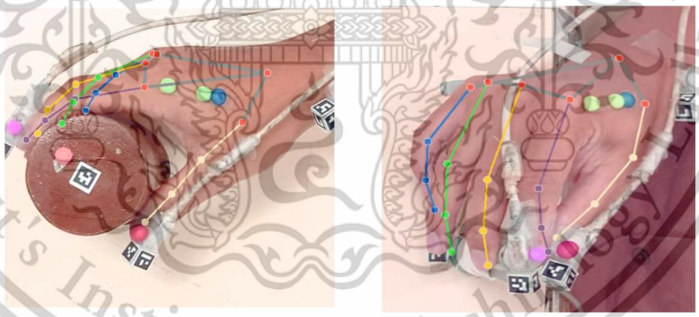

Figure 6 Tracking by Mediapipe

2.4 PnP algorithm

The Perspective-n-Point (PnP) algorithm is a cornerstone technique in computer vision for estimating the pose of a 3D object in a scene relative to a calibrated camera. The term "pose" here refers to the spatial orientation and position of the object, represented by rotation and translation matrices. The "n" in PnP denotes the number of corresponding 2D-3D point pairs used for the estimation. Specifically, the algorithm takes as input a set of 3D points on the object and their corresponding 2D projections in the image. It then computes the rotation and translation that would allow these 3D points to align with the 2D points when projected using the camera's intrinsic parameters

1. Given Data Preparation:

- 3D Points: X_i where i=1,2,...,n
  - $\mathbf{X}_1 = \begin{bmatrix} 1 \\ 2 \\ 5 \end{bmatrix}$
  - $\mathbf{X}_2 = \begin{bmatrix} 2 \\ 3 \\ 6 \end{bmatrix}$
  - $\mathbf{X}_3 = \begin{bmatrix} 3 \\ 1 \\ 4 \end{bmatrix}$
- 2D Points: x_i where i=1,2,...,n
  - $\mathbf{x}_1 = \begin{bmatrix} 320 \\ 240 \end{bmatrix}$
  - $\mathbf{x}_2 = \begin{bmatrix} 400 \\ 300 \end{bmatrix}$
  - $\mathbf{x}_3 = \begin{bmatrix} 450 \\ 350 \end{bmatrix}$

These points correspond such that each 3D point X_i is projected onto the 2D point x_i.

2. Camera Intrinsic Matrix (K):

Defined as:

- $K = \begin{bmatrix} f_x & s & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix}$

- $K = \begin{bmatrix} 1000 & 0 & 300 \\ 0 & 1000 & 200 \\ 0 & 0 & 1 \end{bmatrix}$
- Parameters: $f_x = f_y = 1000, s = 0, c_x = 300, c_y = 200$

Where f_x, f_y are the focal lengths, S is the skew, and (C_X,C_Y) are the coordinates of the optical center.

3. Homogeneous Coordinates Conversion and Camera Matrix Application:

Convert 2D Points into Homogeneous Coordinates:

- $\mathbf{x}_1^h = \begin{bmatrix} 320 \\ 240 \\ 1 \end{bmatrix}$
- $\mathbf{x}_2^h = \begin{bmatrix} 400 \\ 300 \\ 1 \end{bmatrix}$
- $\mathbf{x}_3^h = \begin{bmatrix} 450 \\ 350 \\ 1 \end{bmatrix}$

Apply the Camera Matrix:

$$\mathbf{x}_1' = K\mathbf{X}_1 = \begin{bmatrix} 1000 & 0 & 300 \\ 0 & 1000 & 200 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 2 \\ 5 \end{bmatrix} = \begin{bmatrix} 1300 \\ 2200 \\ 5 \end{bmatrix} \rightarrow \begin{bmatrix} 260 \\ 440 \\ 1 \end{bmatrix}$$

$$\mathbf{x}_2' = K\mathbf{X}_2 = \begin{bmatrix} 1000 & 0 & 300 \\ 0 & 1000 & 200 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 2 \\ 3 \\ 6 \end{bmatrix} = \begin{bmatrix} 2300 \\ 3200 \\ 6 \end{bmatrix} \rightarrow \begin{bmatrix} 383.33 \\ 533.33 \\ 1 \end{bmatrix}$$

$$\mathbf{x}_3' = K\mathbf{X}_3 = \begin{bmatrix} 1000 & 0 & 300 \\ 0 & 1000 & 200 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 3 \\ 1 \\ 4 \end{bmatrix} = \begin{bmatrix} 3300 \\ 1200 \\ 4 \end{bmatrix} \rightarrow \begin{bmatrix} 825 \\ 300 \\ 1 \end{bmatrix}$$

4. Solving for R and t using SVD

- The relationship between the 3D points and their image projections is given by:

$$x_i \sim K[R|t]X_i$$

- Where R is the rotation matrix, t is the translation vector, and $\sim$ denotes equality up to a scale factor.

The equation above can be expanded as:

$$\begin{bmatrix} u_i \\ v_i \\ 1 \end{bmatrix} = K[R|t] \begin{bmatrix} X_i \\ Y_i \\ Z_i \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} 320 \\ 240 \\ 1 \end{bmatrix} = \begin{bmatrix} 1000 & 0 & 300 \\ 0 & 1000 & 200 \\ 0 & 0 & 1 \end{bmatrix} [R|t] \begin{bmatrix} 1 \\ 2 \\ 5 \\ 1 \end{bmatrix}$$

- Here (u_i, v_i) are the pixel coordinates of x_i,

Solving the System by Direct Linear Transform (DLT):Setup the equation $AX=b$ where A is constructed using the elements from each projection equation and b is the flattened vector of the right-hand sides (the 2D point coordinates after being multiplied by the camera matrix).

$$A = \begin{bmatrix} 1 & 2 & 5 & 1 \\ 2 & 3 & 6 & 1 \\ 3 & 1 & 4 & 1 \end{bmatrix}, \quad b = \begin{bmatrix} 260 \\ 440 \\ 1 \\ 383.33 \\ 533.33 \\ 1 \\ 825 \\ 300 \\ 1 \end{bmatrix}$$

Using SVD to solve the homogeneous system and find the parameters in X

Step 1: $AX = B$

$$\begin{bmatrix} 1 & 2 & 5 & 1 \\ 2 & 3 & 6 & 1 \\ 3 & 1 & 4 & 1 \end{bmatrix} X = \begin{bmatrix} 260 \\ 440 \\ 1 \end{bmatrix}$$

Step 2: $(U\Sigma V^T)X = B$

$$\left(\begin{bmatrix} -0.46 & 0.88 & 0.10 \\ -0.66 & -0.37 & -0.65 \\ -0.60 & -0.30 & 0.74 \end{bmatrix} \begin{bmatrix} 11.04 & 0 & 0 \\ 0 & 2.44 & 0 \\ 0 & 0 & 0.75 \end{bmatrix} \begin{bmatrix} -0.27 & -0.42 & -0.87 & -0.11 \\ 0.74 & -0.67 & 0.05 & -0.05 \\ 0.61 & 0.61 & -0.43 & -0.25 \end{bmatrix} \right) X = \begin{bmatrix} -181.66 \\ -30.83 \\ -153.25 \end{bmatrix}$$

Step 3: Multiply Both Sides by U^T

$$\begin{bmatrix} 11.04 & 0 & 0 \\ 0 & 2.44 & 0 \\ 0 & 0 & 0.75 \end{bmatrix} \begin{bmatrix} -0.27 & -0.42 & -0.87 & -0.11 \\ 0.74 & -0.67 & 0.05 & -0.05 \\ 0.61 & 0.61 & -0.43 & -0.25 \end{bmatrix} X = \begin{bmatrix} -181.66 \\ -30.83 \\ -153.25 \end{bmatrix}$$

Step 4: Let $Y = V^T X$

$$\Sigma Y = \begin{bmatrix} -181.66 \\ -30.83 \\ -153.25 \end{bmatrix}$$

Step 5: Solve for Y

$$Y = \Sigma^{-} \begin{bmatrix} -181.66 \\ -30.83 \\ -153.25 \end{bmatrix}$$

$$Y = \begin{bmatrix} 0.0906 & 0 & 0 \\ 0 & 0.4098 & 0 \\ 0 & 0 & 1.3333 \end{bmatrix} \begin{bmatrix} -181.66 \\ -30.83 \\ -153.25 \end{bmatrix} = \begin{bmatrix} -16.47 \\ -12.62 \\ -204.33 \end{bmatrix}$$

Step 6: Solve for X

$$X = VY$$

$$X = \begin{bmatrix} -0.27 & 0.74 & 0.61 \\ -0.42 & -0.67 & 0.61 \\ -0.87 & 0.05 & -0.43 \\ -0.11 & -0.05 & -0.25 \end{bmatrix} \begin{bmatrix} -16.47 \\ -12.62 \\ -204.33 \end{bmatrix} = \begin{bmatrix} 168.75 \\ 98.01 \\ 255.25 \\ 20.57 \end{bmatrix}$$

Assuming X contains parameters representing both rotation and translation, we can decompose it as follows:

X = [rotation and translation parameters]

Typical Form of X

For a 3D to 2D projection, the typical form of the extrinsic parameters might be represented as:

$$X = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \end{bmatrix}$$

Where:

- r_{ij} are the elements of the rotation matrix R.
- t_x, t_y, t_z are the elements of the translation vector t.

Steps to Extract R and t

1. Obtain the Rotation Matrix R: Extract the first 3x3 submatrix from X to get R.
2. Obtain the Translation Vector t: Extract the last column of X to get t.

Given the assumed values, the solution vector X can be correctly decomposed into

$$X_{\text{reshaped}} = \begin{bmatrix} 168.75 & 98.01 & 255.25 & 20.57 \\ -45.32 & 73.12 & 120.25 & 18.93 \\ -30.12 & 55.67 & 110.50 & 22.15 \end{bmatrix}$$

- **Rotation Matrix R:**

$$R = \begin{bmatrix} 168.75 & 98.01 & 255.25 \\ -45.32 & 73.12 & 120.25 \\ -30.12 & 55.67 & 110.50 \end{bmatrix}$$

- **Translation Vector t:**

$$t = \begin{bmatrix} 20.57 \\ 18.93 \\ 22.15 \end{bmatrix}$$

the rotation matrix R and the translation vector t as follows:

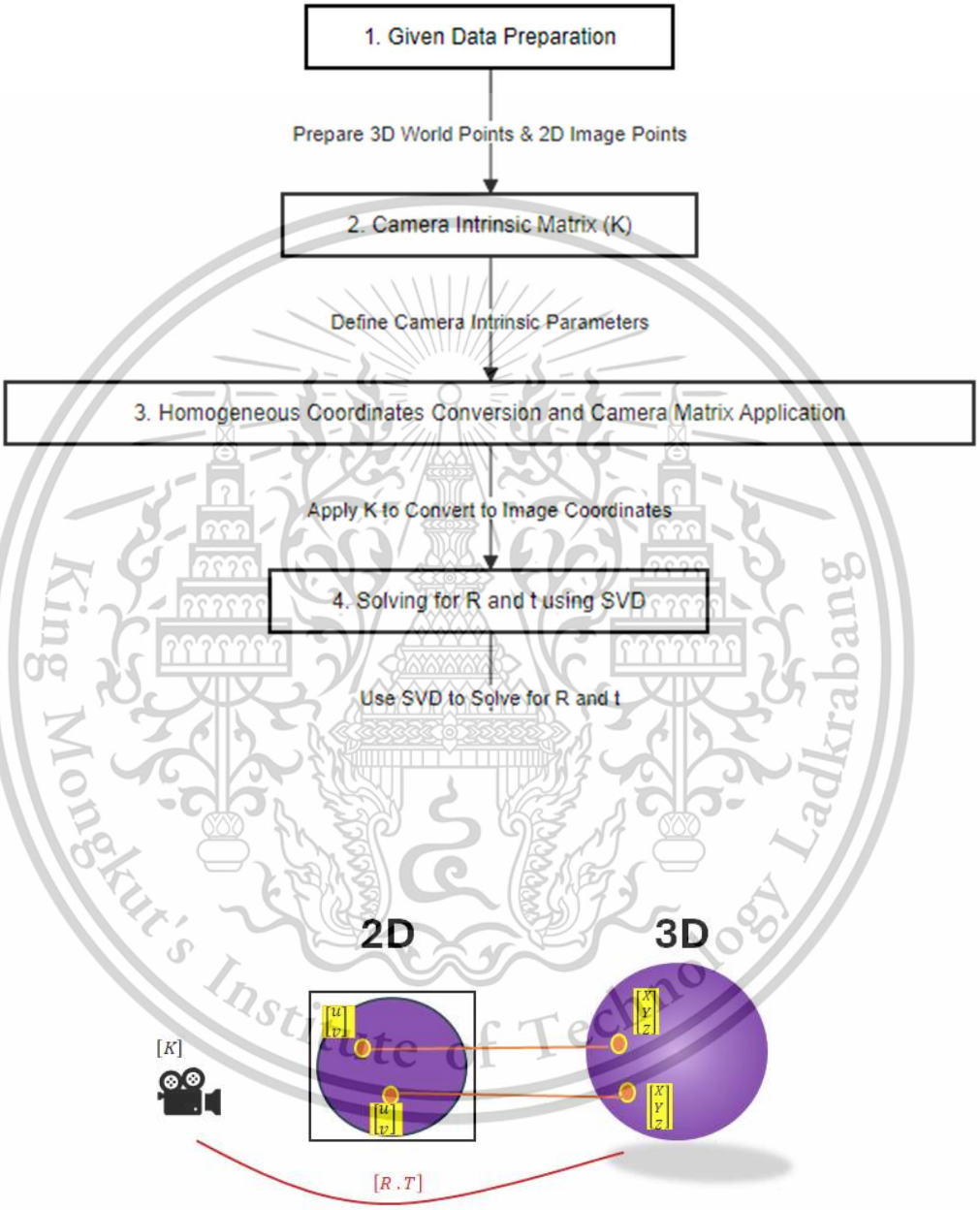

Figure 7 Perspective-n-Point (PnP) algorithm

CHAPTER 3

RESEARCH METHODS

3.1 Camera calibration procedure

Camera calibration using a chessboard pattern is a common method to determine the intrinsic and extrinsic parameters of a camera. This process helps correct lens distortion and improve the accuracy of 3D scene reconstruction. Here's a detailed step-by-step guide on how to perform camera calibration using a chessboard: By following these steps and accurately estimating the necessary parameters, the calibration process can be successfully completed, leading to improved accuracy and reliability in subsequent operations.

Step 1: Prepare the Chessboard

1. **Obtain or create a chessboard pattern**. Use a chessboard with a known number of squares (e.g., 8x8, 9x6). The size of the squares should be measurable, as this is essential for calibration accuracy.
2. **Print the chessboard** on a flat, rigid material to prevent warping during the calibration process.

Step 2: Set Up the Camera

1. **Mount the camera on a stable platform** to minimize movement during the calibration process.
2. **Ensure the entire chessboard is visible** to the camera from various angles and distances.

Step 3: Capture Images

1. **Take multiple photographs of the chessboard** from different angles and distances. Ensure the chessboard fills the frame in some shots and appears in the corners in others to capture a range of distortions.
2. **Capture at least 10-20 images** to cover all parts of the camera's field of view.

Step 4: Image Processing

1. **Convert images to grayscale** to simplify the detection of corners.
2. **Use a corner detection algorithm** like the Harris corner detector or the OpenCV function findChessboardCorners() to identify the internal corners of the chessboard in each image.

Step 5: Camera Calibration

1. **Input the detected corners (image points) and the real-world coordinates of the chessboard corners (object points)** into a camera calibration algorithm.
2. **Use OpenCV's calibrateCamera() function,** which requires object points, image points, and the shape of the image obtained from the camera. This function returns the camera matrix, distortion coefficients, rotation, and translation vectors.

Step 6: Evaluate the Calibration

1. **Check the re-projection error**, which quantifies the accuracy of the calibration. A lower re-projection error indicates a more accurate calibration.
2. **Visualize the results** by using the distortion coefficients and camera matrix to undistort the images and compare them to the original images.

Step 7: Save the Calibration Parameters

1. **Store the camera matrix and distortion coefficients** for future use

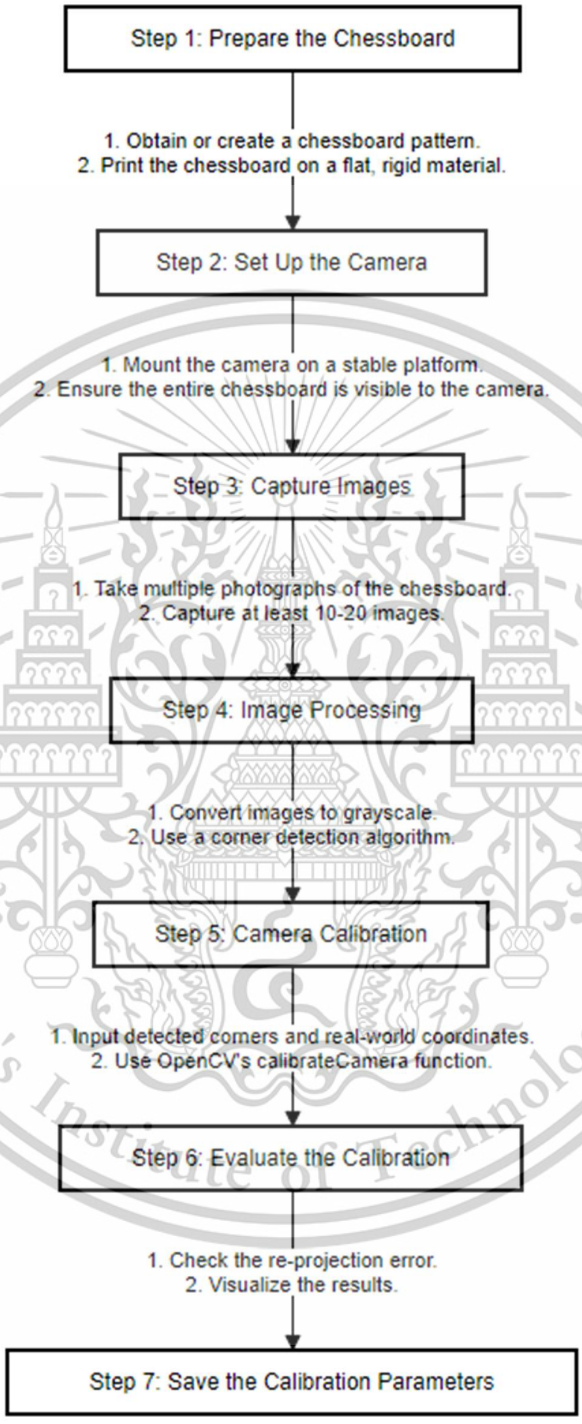

Figure 8 Chessboard for camera calibration

3.2 Preparation for Experiment

As shown in Fig. 7, a participant was asked to sit and place their tested hand on the table at the starting point. The starting point was located 30 centimeters away from the target object, which was a wooden dowel with a diameter of 7.5 centimeters. The participant's hand was equipped with three electromagnetic sensors: two on the tips of the thumb and index fingers, and the third on the radial styloid process. These three sensors were part of the electromagnetic motion tracking system (Motion Monitor, Innsport, Inc, IL, USA [6]). The motion was recorded at a sampling rate of 100 Hz.

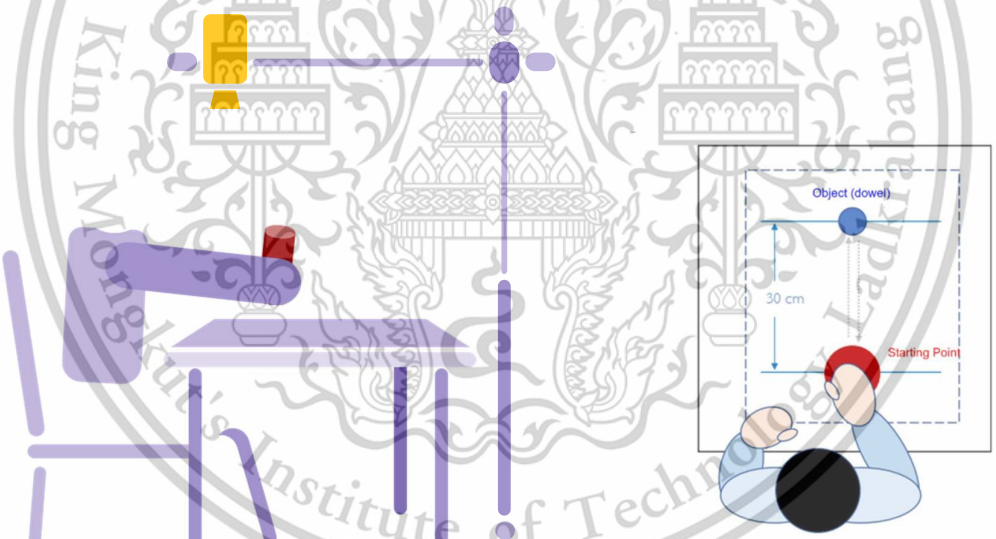

Figure 9 Setup of experiment

The participant's hand was equipped with three electromagnetic sensors: two on the tips of the thumb and index fingers, and the third on the radial styloid process. These three sensors were part of the electromagnetic motion tracking

system (Motion Monitor, Innsport, Inc, IL, USA [6]). The motion was recorded at a sampling rate of 100 Hz.

The participant's hand had four small foam balls of different colors (5-millimeter diameter) attached to it, placed over the latex glove. These balls served as markers for our optical motion capture system, and their positions can be seen in Fig 5. Precisely, the yellow and red balls were positioned at the tips of the thumb and index fingers, respectively. We measured the displacement between these two balls to determine the hand aperture. Additionally, we placed a blue ball on the lateral side of the wrist joint to calculate the hand transport velocity. The two green balls acted as calibrated markers, providing the necessary information to estimate the distance from the camera. Speaking of the camera, was positioned above the table and recorded the movement captured by the optical motion capture system at a rate of 60 frames per second.

Figure 10 The locations of markers for motion capture system

Once the participant heard the "GO" signal, they immediately initiated a sequence of actions, including reaching, grasping, lifting, holding, putting down, releasing the object, and returning their hand to the starting position. This task was repeated for a total of 5 trials. The position data captured by the electromagnetic sensors were then extracted and stored in the computer. Additionally, the video data recorded by the camera underwent an offline conversion process, resulting in a series of static images. The color markers' positions were identified in each of these images and subsequently transformed into 3D coordinates using Python software.

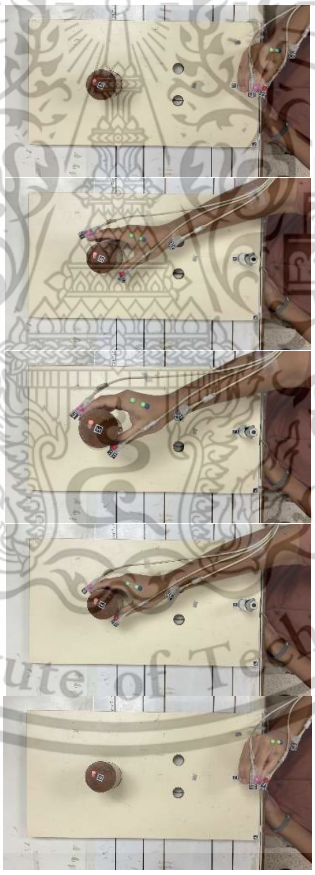

Figure 11 Reach to Grasp motion

3.3 Compute 3D coordinates

This is a step of the program for compute 3D coordinates by Python and Opencv using PnP algorithm and Mediapipe

1. Start: The entry point of the program.

2. Model Points: Initialize a 3D model point matrix to represent the index finger's tip and its thickness.

3. CSV File Setup: Open a new CSV file and write the header for storing the estimated 3D coordinates.

4. Video Capture: Open a video file and prepare to read frames in a loop.

5. While Loop Start: The beginning of the loop that will continuously read video frames and perform hand tracking and 3D pose estimation.

6. Read Frame: Read a single frame from the video file.

7. Hand Tracking: Use MediaPipe to track the hand and get the 2D coordinates of specific landmarks on the index finger.

8. Drawing Landmarks: Utilize MediaPipe's drawing utility to visualize the hand landmarks on the video frame.

9. Intermediate Points: Calculate intermediate 2D points between the detected landmarks to represent the index finger's length and thickness.

10. Pose Estimation: Use the PnP algorithm to estimate the 3D coordinates of the index finger tip based on the 2D image points and 3D model points.

11. CSV Writing: Write the estimated 3D coordinates to the CSV file.

12. Display and Exit: Display the video frame with hand landmarks. The loop breaks if the 'q' key is pressed, leading to file cleanup.

13. File Cleanup: Close the video capture and the CSV file.

14. End: The program terminates.

Each step is crucial for the successful execution of your program, ensuring real-time 3D pose estimation of the index finger.

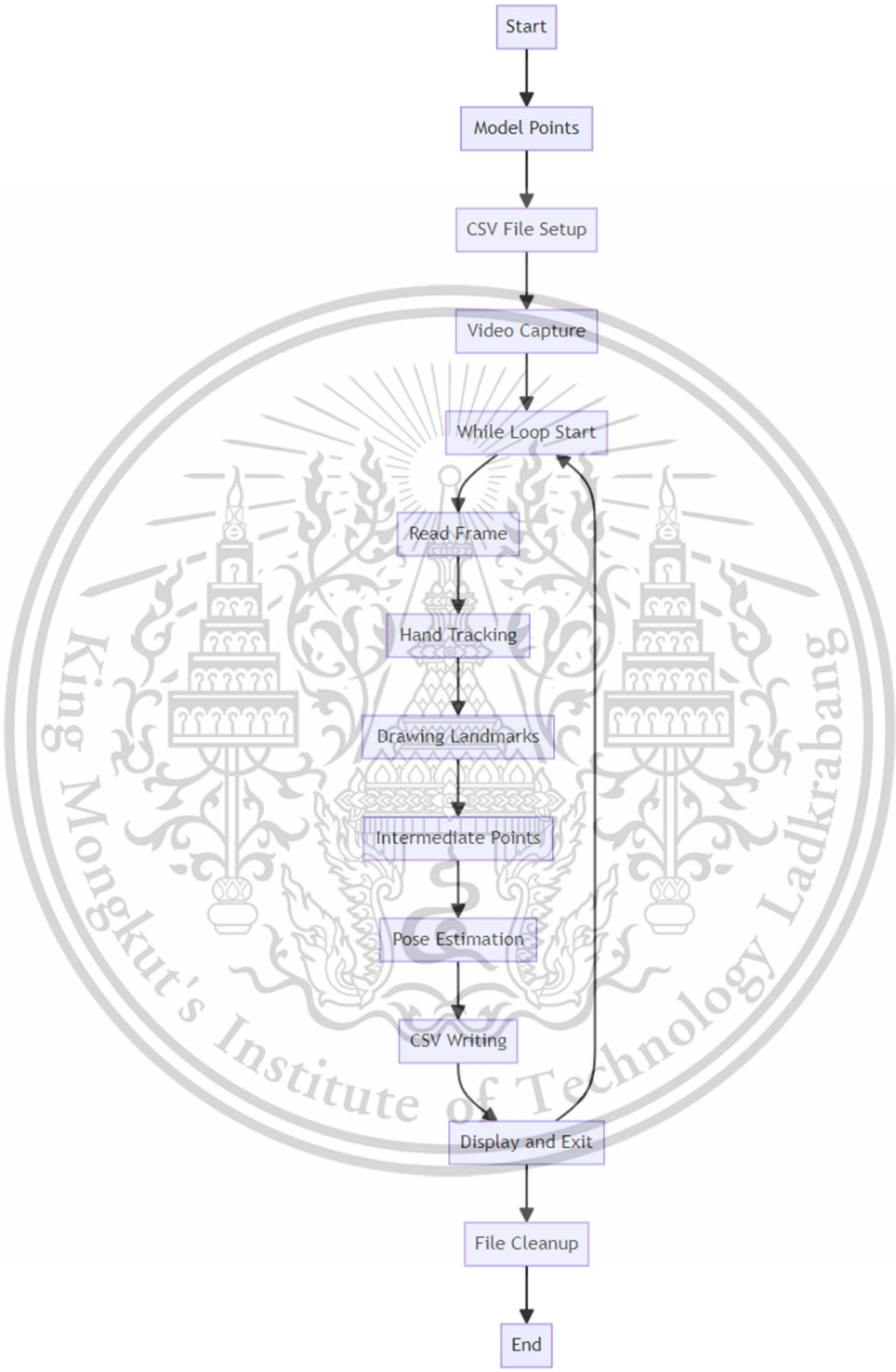

Figure 12 Compute 3D coordinates

3.4 Calculate kinematic parameter

Utilize the 3D coordinates acquired from the Electromagnetic and Single camera systems that consist of Mediapipe and This research to generate graphs depicting the aperture and transport velocity. Subsequently, compare the graphs to identify any similarities and discrepancies between the patterns observed in the three systems.Down sampling of Electromagnetic from 100 Hz to 60 Hz because of smartphone camera that 60 fps

the distance between the thumb and the index finger tip, referred to as the "aperture," is an important measure. It indicates how wide the hand is opened or how the hand shapes itself when preparing to grasp an object.

$$\text{Aperture} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$

transport velocity of the hand movement, indicating how fast and in which direction the hand is moving at each time step.

$$\text{Transport velocity} = \left(\frac{x_{n+1} - x_n}{\frac{1}{60}}\right)\hat{i} + \left(\frac{y_{n+1} - y_n}{\frac{1}{60}}\right)\hat{j} + \left(\frac{z_{n+1} - z_n}{\frac{1}{60}}\right)\hat{k}$$

3.5 Performance measure

Employing both RMSE and MAE ensures a thorough and balanced evaluation of the Mediapipe and Mediapipe + PnP systems against the Electromagnetic reference. This approach allows you to capture both the overall accuracy and the presence of significant errors, as evident in the provided graph. Both metrics provide valuable insights into how closely the systems' 3D coordinate estimations align with the reference system. The data is numerical and continuous, which is appropriate for RMSE and MAE calculations.

RMSE (Root Mean Square Error): This metric measures the average magnitude of the errors between single camera system values and the actual values (reference data). It is suitable for your data because it helps identify how significant the deviations are, giving more weight to larger errors.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}$$

MAE (Mean Absolute Error): This metric measures the average magnitude of the absolute errors between single camera system and the actual values (reference data). It is suitable for your data because it provides a straightforward measure of the average error without squaring the errors, making it easier to interpret.

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i|$$

CHAPTER 4

RESULT AND DISCUSSION

4.1 Aperture

Figure shows how well different methods can track the opening and closing of a hand over time. We used three systems to do this: an electromagnetic system, an optical system using MediaPipe, and another optical system using the PnP algorithm.

All three systems showed similar hand movements, which means they are all reliable for this kind of tracking. But we wanted to know which optical system is more accurate, so we looked at two error measurements: RMSE and MAE.

For the PnP algorithm, the RMSE was 0.2115 and the MAE was 0.1412. For MediaPipe, the RMSE was 0.2186 and the MAE was 0.1448. These numbers tell us that the PnP algorithm is slightly more accurate than MediaPipe. So, if you need to be really precise, the PnP algorithm is more accuracy.

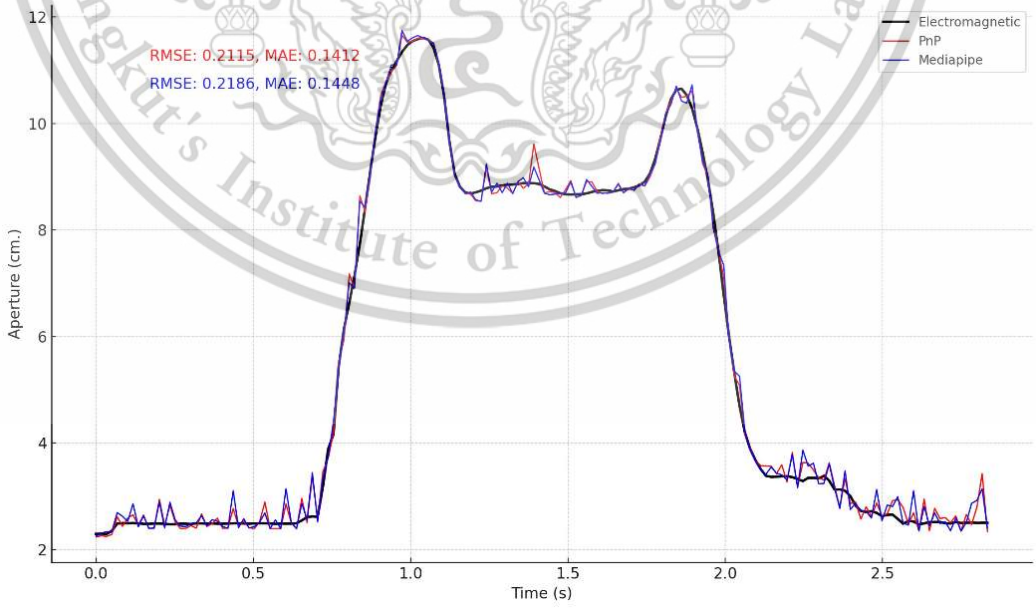

Figure 13 Aperture from three system

4.2 Transport velocity

Figure offers a detailed view of transport velocity of the hand changes over time in this study. We gathered this information by tracking 3D coordinates at a specific point on the wrist, known as the radial stylus, using two different systems. Generally, the hand height patterns from both systems are quite similar, showing only minor differences.

For This research, RMSE = 0.0291 and MAE = 0.0125. For MediaPipe, RMSE = 0.0363 and MAE = 0.0230 These result indicate that this research is slightly more accurate than MediaPipe

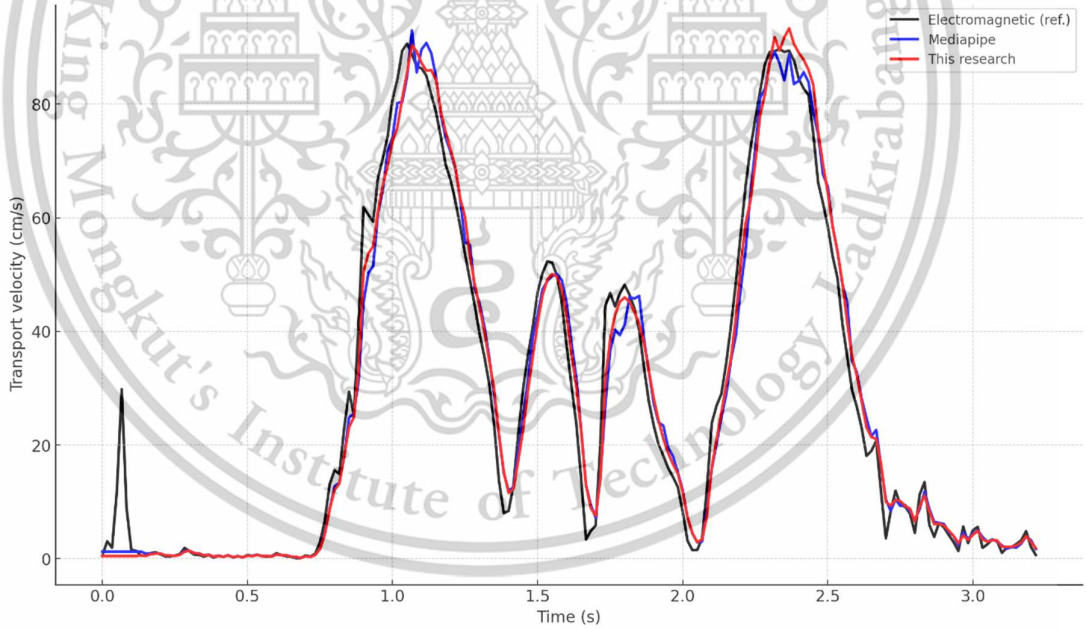

Figure 14 Transport velocity

CHAPTER 5
CONCLUSION AND FUTURE WORK

4.1 Conclusion

The assessment of human movement is a critical aspect of physical therapy management, particularly for evaluating the Reach-to-Grasp (RTG) movement, which is essential for understanding motor skills and therapeutic progress. Traditional Electromagnetic Motion (EM) tracking systems, though highly accurate, are costly and impractical for telemedicine due to their lack of portability and complex setup requirements. This study focuses on developing and implementing a markerless motion tracking system using a single smartphone camera, leveraging the MediaPipe framework and the Perspective-n-Point (PnP) algorithm.

Our research aims to create an accessible, cost-effective, and portable alternative for capturing and analyzing upper extremity movements, specifically the RTG movement. The system is designed to be easy to set up and useful for telemedicine applications, allowing physical therapists to remotely monitor and evaluate patients' motor functions. We conducted a detailed comparison of the kinematic parameters derived from our smartphone-based system with those obtained from a standard EM tracking system to assess performance and accuracy.

The findings suggest that the single smartphone camera system, utilizing MediaPipe and the PnP algorithm, can effectively provide reliable and accurate 3D pose estimations. The kinematic parameters, such as aperture and transport velocity, obtained from our system are comparable to those from the EM tracking system. This indicates that the smartphone-based system can serve as a practical and accessible tool for telemedicine applications, potentially transforming the way physical therapy is delivered and expanding access to healthcare for patients in remote or underserved areas.

4.2 Limitation and Future work

Limitation of this study (Pnp algorithm) is the detection and tracking accuracy of the system are dependent on the performance of the MediaPipe framework. Any limitations or inaccuracies inherent in MediaPipe's hand detection and pose estimation capabilities will directly impact the overall effectiveness of the motion tracking system developed in this study. For our next steps, we plan to make our motion capture system even better. One idea is to add more cameras to capture different angles, which could make the tracking more accurate. We're also thinking about testing our system in real-world settings, like hospitals or rehab centers, to see how well it works outside the lab. Another important area we want to explore is making the system easier to use, so that even people without technical skills can set it up. Lastly, we're interested in seeing how our system performs when tracking other types of movements, not just Reach-to-Grasp. By tackling these areas, we hope to make our system more useful for a wider range of people and situations.

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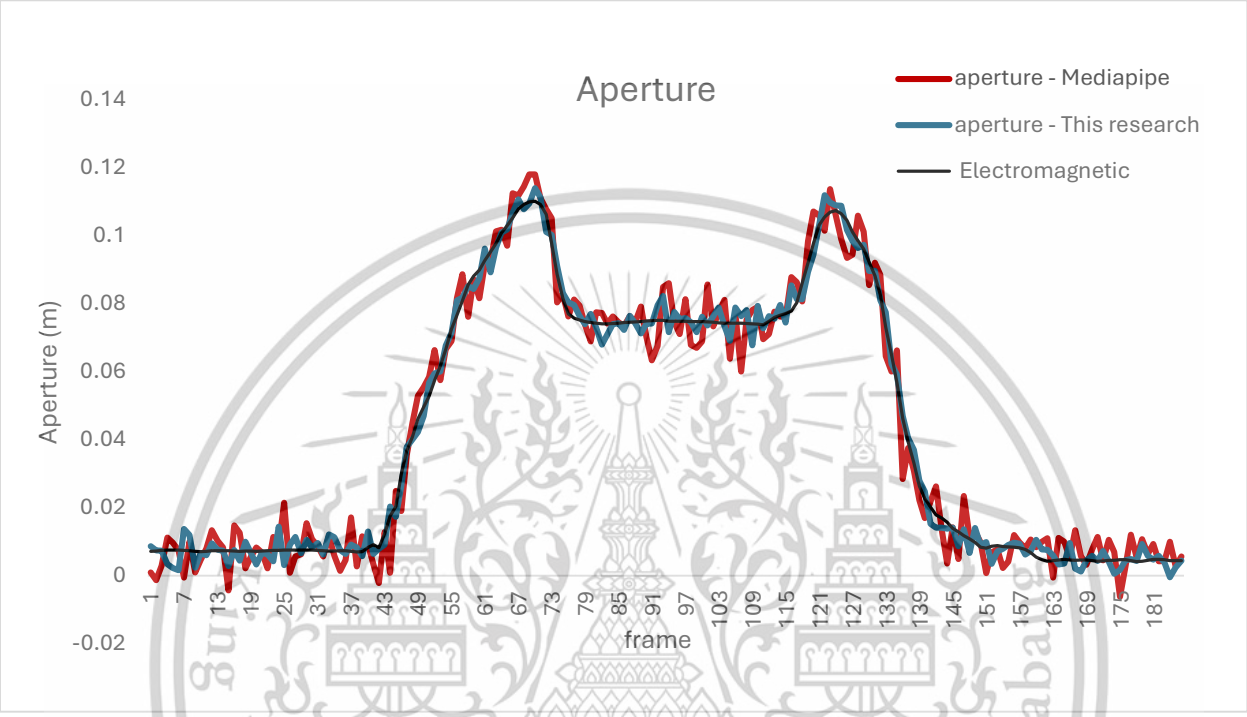
Appendix

Table 1 Result from trial1

frame	Electromagnetic	ectromagne	This research	aperture - This research	- Mediapipe	aperture - Mediapipe
1	0.0051925	0.007098	0.035427862	0.008618873	0.086609752	0.00089207
2	0.007711	0.007258	-0.081611523	0.00740964	0.107787391	-0.001370492
3	0.011113	0.0074265	0.009360357	0.007353365	0.155317846	0.002890555
4	0.0089795	0.0074905	0.036494058	0.003369317	0.089579647	0.011179415
5	0.005771	0.00748	0.040713222	0.002187588	-0.031445098	0.009652807
6	0.0037335	0.007481	0.01225445	0.001593464	0.189932595	0.007399163
7	0.0055695	0.0074105	-0.015293034	0.013682399	-0.096209294	-0.000611357
8	0.005506	0.007273	-0.016679419	0.011903189	-0.043558961	0.009947286
9	0.0133615	0.0071325	0.00894649	0.002285662	-0.092152148	0.000888195
10	0.016444	0.0070155	-0.026045116	0.006554423	0.128992911	0.004550383
11	0.007503	0.007107	-0.019271551	0.006040163	0.161734984	0.007961393
12	0.007899	0.0072715	0.091846147	0.00948523	-0.084853224	0.013390467
13	0.004314	0.007338	0.010695549	0.007608859	-0.042771429	0.010198939
14	0.006294	0.007335	-0.041313106	0.007281684	0.19345062	0.008273778
15	0.0038815	0.0073035	0.000597948	0.002821084	0.00041345	-0.00439857
16	0.0039215	0.0072175	0.002277553	0.007498358	0.1607704	0.01477978
17	0.00421	0.007166	0.014927445	0.004438831	-0.005228661	0.01262786
18	0.004548	0.007185	0.031112733	0.009956933	0.009037902	0.002141939
19	0.003746	0.0071985	0.060159765	0.006694542	0.090214441	0.005520979
20	0.003441	0.007149	-0.015606764	0.003283507	0.003134493	0.008262826
21	0.0033805	0.0071785	0.029539912	0.006749298	-0.00937771	0.00670598
22	0.0046955	0.007346	0.018989535	0.006256396	-0.145368566	0.00211803
23	0.006498	0.007446	0.040824692	0.004197812	0.078796394	0.011376037
24	0.005585	0.007454	-0.021611124	0.014402193	-0.011907556	0.008769418
25	0.005903	0.0074745	-0.007921784	0.00305372	0.017576692	0.021496929
26	0.00352	0.007487	0.059889084	0.009082474	0.03154324	0.000770589
27	0.003309	0.007471	0.009616604	0.011375561	-0.05178943	0.005631379
28	0.008189	0.007517	0.047277347	0.006525674	-0.038842715	0.006296786
29	0.008479	0.007535	0.014494177	0.010533658	0.175366297	0.015389282
30	0.005307	0.007494	0.081224003	0.008140929	-0.046303806	0.010740523
31	0.003924	0.0073965	-0.046323987	0.009586593	0.018741724	0.008738438
32	0.001988	0.007309	-0.005593422	0.006207329	-0.061837217	0.005643541
33	0.000535	0.0072585	-0.067243086	0.012133923	0.102525918	0.011622629
34	0.0040405	0.007263	0.008194648	0.011319423	-0.02475175	0.005840116
35	0.005183	0.007319	-0.034719619	0.007516387	0.084803269	0.001407265
36	0.004623	0.0073265	0.052975099	0.006330098	-0.057946589	0.004599601
37	0.0204375	0.0071305	-0.032042067	0.009071742	0.024563257	0.017150303
38	0.044681	0.006965	0.036893594	0.008271377	-0.011077675	0.002740449
39	0.09289	0.007044	0.215337018	0.005751126	0.130034916	0.011589191
40	0.151067	0.0082375	0.229373813	0.012953435	0.09194102	0.009152616
41	0.148553	0.009116	0.101951654	0.006403015	0.019618492	0.003290246
42	0.173877	0.0081705	0.216690519	0.007841298	0.0243056	-0.002229637
43	0.2795175	0.0123045	0.219335014	0.009097035	0.289493366	0.012750571
44	0.268316	0.017511	0.24663249	0.020307605	0.201760085	0.00077278
45	0.298507	0.0203455	0.279233808	0.017322376	0.404019256	0.024976845
46	0.5498575	0.0298405	0.590069251	0.026355036	0.670171296	0.019033132
47	0.630395	0.036761	0.671731225	0.037814006	0.437896285	0.035378329
48	0.592199	0.040908	0.615623008	0.040107037	0.663372808	0.045064093
49	0.6361875	0.0461565	0.6407511	0.042327344	0.644056847	0.052945921
50	0.696537	0.049674	0.714273154	0.047024598	0.670290623	0.055465391
51	0.7151505	0.0528015	0.773493013	0.056761408	0.676104666	0.058500557
52	0.783762	0.057458	0.846874583	0.059508205	0.714679421	0.06643683
53	0.825761	0.061697	0.858087842	0.060112507	0.793630322	0.057522438
54	0.862491	0.0665955	0.881007823	0.067760868	0.897009539	0.066660319
55	0.905407	0.072609	0.9088699	0.071468315	0.880448397	0.069087457
56	0.899281	0.076728	0.915971423	0.081057354	0.896932012	0.081821641
57	0.8792995	0.0808835	0.900235864	0.081845435	0.757646591	0.088771034
58	0.8634245	0.085685	0.850350481	0.085301971	0.883776337	0.076182349
59	0.860038	0.088148	0.83028265	0.084375267	0.924039076	0.087277601
60	0.838751	0.0899915	0.951440337	0.087583374	0.717814068	0.081714461
61	0.799381	0.092832	0.743735	0.096247799	0.811611671	0.091680421
62	0.768312	0.09532	0.723744937	0.089273171	0.812089122	0.092760629
63	0.722831	0.097835	0.688534775	0.096594317	0.790853794	0.101384972
64	0.677786	0.100887	0.733970583	0.101041722	0.71762062	0.101834109
65	0.651867	0.103053	0.660127948	0.101913191	0.693027911	0.097145303
66	0.6138975	0.105315	0.609301529	0.10683151	0.654100518	0.112591731
67	0.557826	0.107938	0.569212243	0.110766477	0.561015169	0.111900982
68	0.514758	0.10927	0.477033949	0.107896777	0.521011096	0.114581366
69	0.4754335	0.110028	0.494647125	0.109553922	0.441351722	0.118207393
70	0.4183735	0.1102465	0.466619348	0.11419095	0.23650033	0.11812903
71	0.376723	0.109344	0.356964154	0.11134307	0.303345781	0.111171554
72	0.3405735	0.1063395	0.326966341	0.101194823	0.437958669	0.107841716
73	0.271569	0.0978045	0.254690928	0.100362932	0.198324366	0.105246495
74	0.195759	0.088765	0.182406137	0.091186599	0.195488661	0.080431993
75	0.112838	0.081646	0.14547598	0.083236182	0.077682882	0.083034521
76	0.0802055	0.077107	0.104469603	0.080493212	-0.047777701	0.076295597
77	0.094986	0.075865	0.151614193	0.079663417	0.119687456	0.081336769
78	0.1589665	0.0752525	0.062986708	0.07653434	0.077944412	0.079556618
79	0.2631495	0.0747825	0.231149597	0.074093637	0.071859401	0.073912201
80	0.327018	0.074556	0.410161958	0.077039569	0.317396006	0.068965267
81	0.3731235	0.0743165	0.348875575	0.072995847	0.339801238	0.077550301
82	0.440057	0.074121	0.415156159	0.068024888	0.468076119	0.077333167
83	0.486621	0.074184	0.490594912	0.071032679	0.469835812	0.074281915
84	0.509638	0.07421	0.515267307	0.074005576	0.458428847	0.076350943
85	0.524914	0.0743115	0.538538355	0.074331133	0.558996075	0.074640132
86	0.513088	0.074494	0.619619331	0.07235256	0.570502281	0.073514744
87	0.485986	0.0746225	0.483310463	0.076488683	0.564247254	0.076363712
88	0.417844	0.0747775	0.408764099	0.074794077	0.346044803	0.074641138
89	0.344922	0.074832	0.367219853	0.071337718	0.286965898	0.079187867
90	0.284961	0.074966	0.307939211	0.074175292	0.417869623	0.07031348
91	0.193037	0.0751085	0.153715739	0.074224462	0.143891466	0.063362628
92	0.094565	0.075189	0.086147673	0.079638383	0.242668815	0.067652787
93	0.0329715	0.0751415	0.077558502	0.082319076	0.109941107	0.084963862
94	0.053134	0.074911	0.063507792	0.07168821	-0.201535263	0.086090882
95	0.088215	0.074852	0.130373933	0.077604551	0.003709726	0.074676027
96	0.284528	0.0749365	0.301556991	0.075521513	0.226012882	0.071139618
97	0.4714825	0.0749	0.48356828	0.075835192	0.368226477	0.081385296
98	0.451522	0.074843	0.381231139	0.074629794	0.54376567	0.067877556
99	0.449528	0.0748365	0.426124076	0.071678632	0.392095964	0.067031398
100	0.4762745	0.0747595	0.433873882	0.076199372	0.630973314	0.069003601
101	0.478254	0.074749	0.35409043	0.073627235	0.62200998	0.085737911
102	0.458132	0.0746575	0.503772799	0.076410818	0.487280232	0.073344628
103	0.4251145	0.0744525	0.422808233	0.078936597	0.391009765	0.077489253
104	0.379951	0.074362	0.344730572	0.07350985	0.522878921	0.081238908
105	0.3185905	0.0743535	0.254744299	0.069137582	0.403602556	0.06387778
106	0.2564655	0.0743455	0.265950078	0.078916851	0.288167703	0.077298223
107	0.220782	0.074295	0.204263488	0.07640719	0.179355562	0.060081236
108	0.1958105	0.074197	0.197527109	0.078192677	0.157370075	0.075327828
109	0.1712745	0.0741685	0.142650975	0.067866505	0.066414571	0.078178598
110	0.153114	0.074027	0.096285786	0.079447863	0.20416585	0.079123311
111	0.1398535	0.0738495	0.109418279	0.072833663	0.176898364	0.069621279
112	0.1089955	0.0748945	0.022144068	0.076359983	0.096860303	0.071143537
113	0.06221	0.076056	0.070580079	0.075620232	0.16784924	0.077677248
114	0.026151	0.07665	0.054832412	0.079668895	0.021498774	0.076336349
115	0.0142665	0.0771285	0.00803537	0.074491156	0.102039647	0.075989466
116	0.019028	0.077946	0.042887782	0.085438319	0.033353689	0.087871788
117	0.0524455	0.080409	0.023168328	0.081357166	0.150994854	0.086394231
118	0.177836	0.086218	0.161063047	0.08143874	0.272386962	0.080736154
119	0.258142	0.092008	0.256220946	0.08936836	0.274296997	0.098444314
120	0.2725885	0.0978315	0.226497193	0.0944627	0.236270799	0.107266317
121	0.3122265	0.103284	0.31076627	0.103336378	0.3596924	0.106092962
122	0.366354	0.105597	0.342914816	0.112063123	0.472036375	0.101565222
123	0.428504	0.106996	0.471871119	0.109884356	0.442563895	0.113784503
124	0.523263	0.1075	0.485998221	0.108969837	0.390313457	0.106036883
125	0.600404	0.106593	0.56011717	0.108880639	0.668094714	0.099002489
126	0.6718225	0.1045795	0.669194154	0.101710106	0.575306984	0.093549531
127	0.744165	0.101233	0.765811248	0.098551792	0.688058801	0.094488045
128	0.78951	0.098663	0.731891389	0.096485264	0.824590193	0.106027499
129	0.833868	0.0961655	0.832140901	0.097456728	0.952672057	0.10131521
130	0.8824335	0.092333	0.920116834	0.089670964	1.067505507	0.085553649
131	0.892171	0.088375	0.917759372	0.089802666	0.898819434	0.092108931
132	0.894726	0.0827075	0.929735889	0.081134593	0.848648036	0.08854767
133	0.8944535	0.073095	0.923086782	0.077540366	0.960916378	0.064598697
134	0.89295	0.065005	0.869566111	0.062363723	0.871595245	0.06010372
135	0.891248	0.0567645	0.862570327	0.059183079	0.815670579	0.066305865
136	0.8636995	0.046335	0.770758616	0.047002521	0.896474897	0.028445968
137	0.836519	0.039353	0.841474011	0.04046738	0.85218012	0.037594359
138	0.8269925	0.0330955	0.743197302	0.037038807	0.878201855	0.030894477
139	0.793568	0.0263195	0.78207021	0.027949563	0.772433169	0.022238983
140	0.71974	0.022692	0.82846568	0.024710244	0.764021168	0.016922469
141	0.653788	0.0200975	0.661104569	0.015206434	0.595468969	0.021837854
142	0.612981	0.017875	0.603058605	0.014109396	0.654679035	0.026291679
143	0.56695	0.016975	0.58900634	0.014105659	0.604678766	0.013405272
144	0.526937	0.0156815	0.508437158	0.013862305	0.453791054	0.003556919
145	0.464138	0.0139325	0.397908444	0.014069004	0.616413637	0.014194297
146	0.395168	0.012846	0.351959907	0.0086442	0.403235816	0.004850717
147	0.3454955	0.0117625	0.324372817	0.013640879	0.367882265	0.023456148
148	0.2829515	0.0108195	0.269074421	0.006640136	0.354622792	0.011305693
149	0.261639	0.009752	0.182188716	0.013978476	0.214520268	0.013006522
150	0.219378	0.008319	0.257691017	0.009001545	0.135758752	0.00987284
151	0.1802965	0.008075	0.212112568	0.009873929	0.138764225	0.000759091
152	0.19858	0.00866	0.219451288	0.003481211	0.244852353	0.006823172
153	0.194613	0.0088035	0.168393548	0.007140829	0.305746483	0.007703931
154	0.078922	0.008498	0.10380922	0.007922863	0.030427506	0.00222879
155	0.040578	0.00842	0.047007438	0.009040824	-0.050046113	0.004142116
156	0.091574	0.0083135	0.091126266	0.009662453	0.153250135	0.011909388
157	0.110623	0.008172	0.110278638	0.009375819	0.185217498	0.009766736
158	0.093796	0.00774	0.100544321	0.006149221	0.082761521	0.008033073
159	0.0905625	0.0067555	0.107416802	0.007262623	0.082462613	0.01063289
160	0.0623945	0.005436	-0.040239058	0.010492752	0.132624498	0.008359171
161	0.055414	0.004722	0.099931417	0.007724631	-0.027071099	0.009911585
162	0.120052	0.0042155	0.038184383	0.007626191	0.112060666	0.011040307
163	0.1087785	0.0043515	0.14534949	0.005867158	0.167319522	-0.000580984
164	0.048048	0.004588	0.048641944	0.003269729	0.00565826	0.011065536
165	0.0428975	0.004747	0.066765247	0.003566761	-0.043750578	0.009916275
166	0.0627995	0.004541	0.034898138	0.00958868	-0.052210017	0.005182098
167	0.051037	0.004506	0.105018034	0.002001951	0.012022146	0.013364562
168	0.040942	0.0045515	0.123571379	0.001201028	0.192620852	0.005743284
169	0.0182535	0.004625	0.006083257	0.004512939	0.180017995	0.00315801
170	0.027557	0.004422	0.024373525	0.005829039	0.006687638	0.00764817
171	0.0511555	0.004196	0.082438073	0.004311216	0.123984223	0.011347666
172	0.0278985	0.0043205	0.027649159	0.007264257	-0.018958497	0.004451194
173	0.064618	0.004455	0.144489807	0.00408698	0.08117429	0.010482264
174	0.047483	0.00447	0.047340063	0.000519128	0.130461135	0.006902884
175	0.020897	0.0046745	0.000912039	0.001649256	-0.015660999	-0.006169472
176	0.026089	0.004686	-0.01699218	0.004474774	-0.019067521	0.002611981
177	0.0351255	0.0043755	0.103335482	0.00485402	0.058115671	0.012055625
178	0.0231425	0.0041635	0.024342562	0.004290398	0.139192559	0.005302365
179	0.010964	0.004232	-0.048028249	0.009277981	-0.054335683	0.010725957
180	0.018574	0.0045235	0.012694708	0.005816321	0.043057695	0.00642129
181	0.022513	0.0047565	0.06691158	0.004669221	-0.073789771	0.009320479
182	0.02464	0.004734	0.039442718	0.00579464	-0.040613617	0.004196605
183	0.0364965	0.004656	-0.045861561	0.003869518	0.085422381	0.004288567
184	0.04188	0.00442	0.00186379	-0.000436854	0.123833208	0.00999725
185	0.01581	0.004353	0.049247418	0.002434275	0.038430546	0.002699514
186	0.004382	0.004422	0.055621229	0.004360874	-0.027036959	0.005649622
			RMSE	0.043358254	0.002965466	0.082142334	0.005921613
			MAE	0.033528583	0.002395887	0.066358672	0.00477836



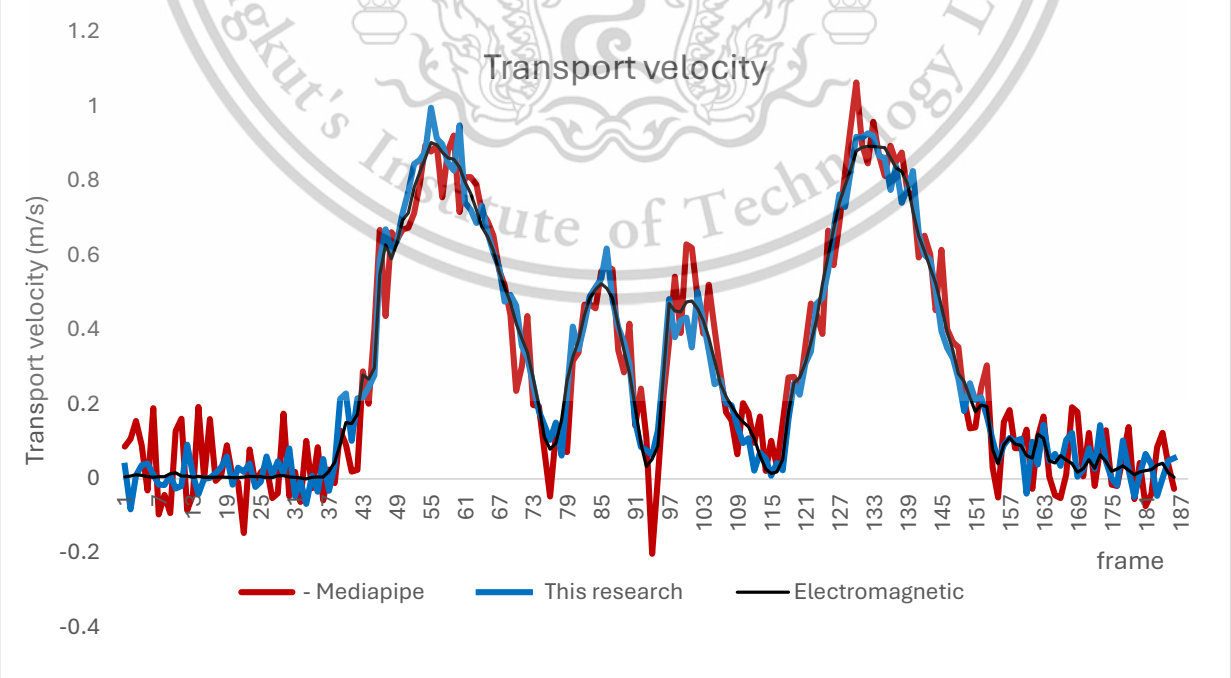
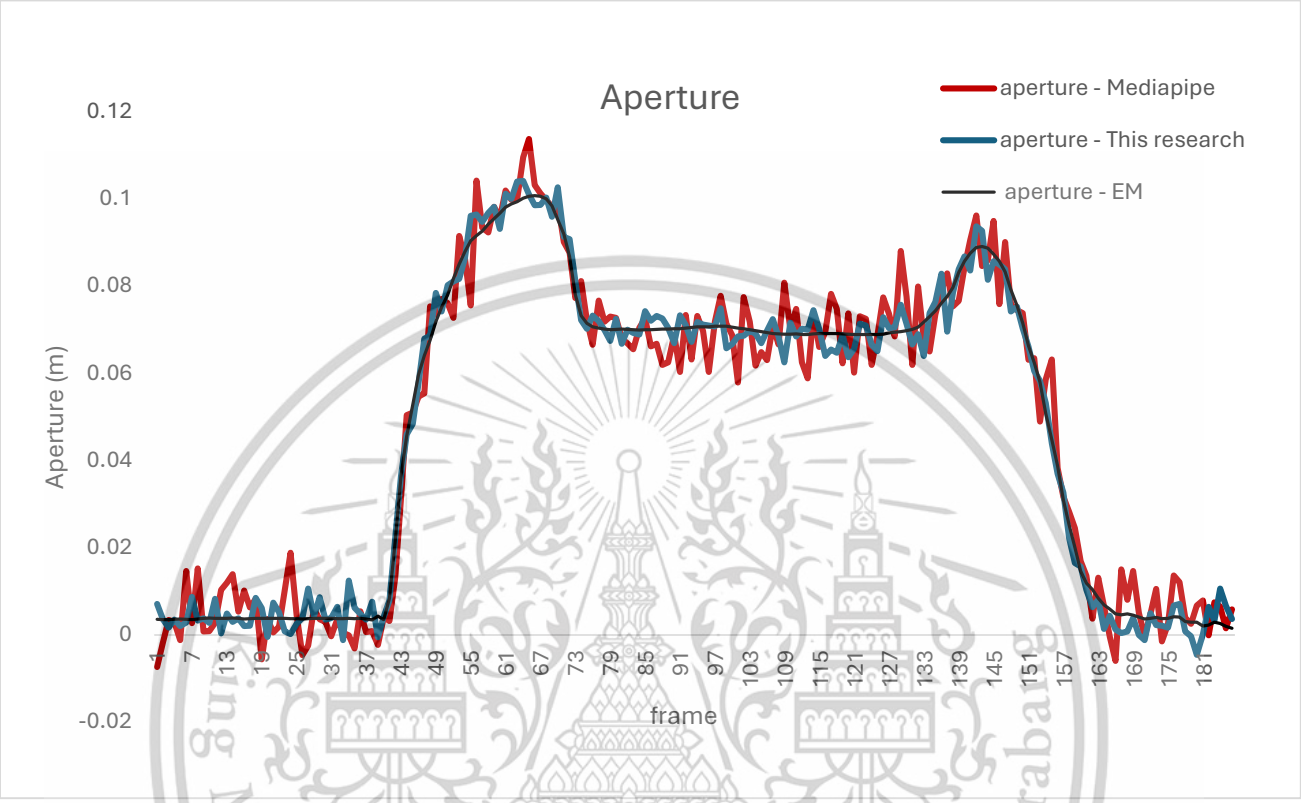


Table 2 Result from trial2

frame	velocity - EM	aperture - EM	This research	aperture - This research	- Mediapipe	aperture - Mediapipe
1	0.0035985	0.003537	0.04046521	0.007098059	0.137446117	-0.007367924
2	0.005277	0.003498	-0.006963419	0.003537085	-0.033716382	-0.001813061
3	0.0027115	0.0034715	0.042510527	0.001632468	0.117408093	0.003448935
4	0.0056715	0.0035865	-0.041239678	0.003492305	0.037601263	0.002899757
5	0.005842	0.003653	0.029235744	0.00205422	-0.020686191	-0.001195342
6	0.005547	0.003541	-0.052283929	0.002822445	0.107998108	0.01468178
7	0.003667	0.0034755	0.012130893	0.008698404	0.032603617	0.002710657
8	0.005697	0.003652	0.023119897	0.003238265	0.066707011	0.01526879
9	0.0085575	0.0038095	-0.017370084	0.003791838	0.069107172	0.000800063
10	0.0050725	0.0038205	-0.029331798	0.002787103	0.085447294	0.000838102
11	0.002517	0.003779	0.061656549	0.008281617	0.196220346	0.002764688
12	0.0041475	0.003773	0.001762347	0.000357288	-0.006485295	0.010319704
13	0.006005	0.0037495	0.06876933	0.00489869	-0.155340934	0.011932231
14	0.007457	0.003824	0.007714781	0.002941661	0.175379146	0.013916844
15	0.0050625	0.003784	-0.010052122	0.003793692	-0.053424063	0.005297795
16	0.005725	0.003643	-0.045837402	0.002033475	-0.008607799	0.010207056
17	0.006351	0.003722	-0.055646292	0.002082335	0.054367253	0.006294772
18	0.008375	0.003783	-0.017958012	0.008483867	0.134564885	0.008275132
19	0.0055355	0.0037505	0.093287597	0.006107058	0.029030619	-0.005653892
20	0.002069	0.00376	-0.015592253	-0.000452084	0.083961021	0.003610938
21	0.0031745	0.003793	0.022314624	0.007359211	-0.019708743	0.000538791
22	0.0033265	0.003781	-0.015879005	0.005215534	0.191395455	0.00188995
23	0.002396	0.00375	0.061373704	0.000784582	-0.015261727	0.01035567
24	0.001099	0.0037315	0.028438928	0.000175511	0.068632272	0.01883668
25	0.0031205	0.003683	-0.011086979	0.00254956	-0.001338246	0.004529541
26	0.005003	0.003657	0.026534062	0.003822584	0.059121212	-0.004697702
27	0.006603	0.0037125	0.037676803	0.010610955	0.012724838	-0.00248327
28	0.0061095	0.0038085	-0.093415649	0.004217871	0.059060952	0.005882355
29	0.002606	0.003807	-0.014639913	0.008619454	0.002655889	0.003598829
30	0.004221	0.0037665	0.130332182	0.003504809	0.074598953	0.003010333
31	0.0024935	0.003749	-0.036065118	0.003873965	0.056791472	-0.000298051
32	0.001305	0.003705	-0.066975972	0.006396627	0.042906622	0.003551763
33	0.0071585	0.0037055	0.068971185	-0.001202827	-0.091363986	0.000481036
34	0.0239	0.0037515	0.053707797	0.01248356	0.106754304	-0.000122499
35	0.056738	0.003704	0.006166591	0.006199248	0.142627243	-0.003155415
36	0.070393	0.0038125	0.041573628	0.004838703	-0.019761549	0.005381433
37	0.0996575	0.0036545	0.071223321	0.003509541	0.016926743	0.000600611
38	0.182132	0.003385	0.184610363	0.007630552	0.084617865	0.000817179
39	0.266225	0.0043215	0.341495222	-0.000542845	0.1316963	-0.002346216
40	0.326251	0.0034635	0.274456839	0.004174625	0.359124738	0.004007343
41	0.260218	0.00832	0.3868112	0.00790074	0.290515315	0.003202001
42	0.2717115	0.021458	0.177452823	0.022169232	0.361446096	0.013119166
43	0.547997	0.036429	0.499323935	0.036451265	0.496641579	0.031202767
44	0.682355	0.045694	0.649786509	0.046041383	0.649694208	0.050462346
45	0.6607115	0.0528785	0.687443598	0.048475408	0.54725551	0.051075213
46	0.590675	0.0598045	0.633879224	0.057882064	0.646206228	0.054695
47	0.586543	0.064131	0.553650977	0.068025077	0.443010622	0.055426964
48	0.641808	0.067651	0.69363411	0.068701092	0.627290414	0.075433634
49	0.6995675	0.071906	0.761394698	0.078556269	0.783165874	0.073568849
50	0.757259	0.075259	0.705594712	0.074263864	0.863850306	0.077122559
51	0.794949	0.078112	0.792793091	0.080328968	0.819184244	0.076205015
52	0.793097	0.0818085	0.865599897	0.081165863	0.728206007	0.072770269
53	0.793328	0.085164	0.728673237	0.081766905	0.757749345	0.091579378
54	0.790934	0.0880305	0.794400389	0.086523286	0.855444998	0.086475097
55	0.78675	0.090542	0.816807754	0.096226139	0.791835635	0.075685624
56	0.774923	0.091707	0.85362981	0.096542377	0.717971182	0.1043056
57	0.752804	0.0927475	0.787577555	0.094834511	0.622720131	0.093519737
58	0.7056925	0.09432	0.665349864	0.096884729	0.651796424	0.092416741
59	0.665437	0.095567	0.64167028	0.098290333	0.697468359	0.098275684
60	0.64914	0.0968355	0.641347853	0.09321493	0.673218894	0.095761892
61	0.630996	0.0982605	0.654134299	0.101312088	0.610144845	0.102023205
62	0.600461	0.098974	0.578398944	0.100128105	0.565257659	0.099914713
63	0.5665705	0.0995035	0.545910889	0.104074714	0.54063384	0.100020795
64	0.513822	0.100263	0.527757679	0.104318576	0.433502601	0.109724095
65	0.481712	0.100732	0.430600638	0.101189227	0.394778986	0.113928226
66	0.446552	0.1009065	0.488761245	0.098664221	0.46044124	0.103337114
67	0.391948	0.1007465	0.428699416	0.098737267	0.433721763	0.101356696
68	0.345222	0.100108	0.322663658	0.10046492	0.354208648	0.09981528
69	0.302374	0.0985445	0.308216541	0.096004135	0.306903833	0.098391892
70	0.266406	0.0953295	0.213950607	0.102768343	0.388050059	0.099148776
71	0.246084	0.092058	0.240103722	0.091398304	0.320614395	0.090249536
72	0.211871	0.0868375	0.248144431	0.090878638	0.410397768	0.087815718
73	0.144167	0.078075	0.254790462	0.081274338	0.145943913	0.077319626
74	0.094568	0.07328	0.084597568	0.072250739	0.09895844	0.081238388
75	0.055641	0.0715845	0.103578636	0.070325955	0.093931287	0.07221385
76	0.057155	0.070763	0.073204782	0.073279415	0.090914449	0.066644343
77	0.075402	0.070412	0.142924933	0.072092248	0.124159567	0.076733361
78	0.104202	0.0701965	0.194334888	0.070022335	0.040610175	0.071928218
79	0.1810165	0.0700815	0.144416263	0.067531521	0.301435006	0.073109373
80	0.241718	0.070173	0.15851214	0.072588937	0.166093702	0.072799429
81	0.2961185	0.0702285	0.350130284	0.066878649	0.11975478	0.068068365
82	0.3861715	0.070157	0.417381488	0.070111021	0.478520048	0.066955344
83	0.442924	0.070073	0.496974877	0.069355443	0.410403606	0.065613381
84	0.486657	0.070042	0.512889146	0.069013003	0.503802741	0.070536508
85	0.5220865	0.0700565	0.541905458	0.074333588	0.623463285	0.072717426
86	0.538228	0.070071	0.469628655	0.072136007	0.568931949	0.066281866
87	0.550659	0.0701275	0.635424921	0.073253753	0.456530288	0.066830182
88	0.543213	0.0702165	0.453981047	0.072639421	0.683202629	0.062015298
89	0.522994	0.070253	0.583758919	0.070539787	0.447701948	0.062588663
90	0.5027165	0.0702675	0.495011484	0.067014182	0.415238844	0.068921872
91	0.453207	0.07032	0.455762697	0.073395358	0.480392009	0.060341361
92	0.407418	0.070444	0.440975533	0.071144821	0.369888244	0.073472644
93	0.3604695	0.070585	0.343306873	0.067283997	0.667777882	0.063234019
94	0.275702	0.070718	0.214125954	0.071826119	0.235560171	0.073230125
95	0.214102	0.07076	0.229571725	0.071239852	0.274644562	0.069779613
96	0.1502595	0.0707725	0.273912117	0.071041463	0.150656756	0.060351082
97	0.061543	0.0708735	0.098678325	0.070830445	0.005468202	0.071898257
98	0.038754	0.070874	0.056487106	0.07500576	0.041689576	0.077863548
99	0.04357	0.070854	0.102760127	0.065806016	-0.050458883	0.071451838
100	0.124831	0.070695	0.153299262	0.066759985	-0.051782392	0.068837118
101	0.330651	0.070473	0.335198887	0.06854605	0.352283974	0.057974688
102	0.430195	0.070316	0.409925982	0.06868917	0.604398906	0.077544721
103	0.382657	0.0700845	0.385274731	0.069753744	0.400528248	0.071948825
104	0.392885	0.069857	0.35363473	0.069222348	0.443102976	0.061866476
105	0.434172	0.0696685	0.372754986	0.066988699	0.327738959	0.064949118
106	0.450096	0.069402	0.436308807	0.069845827	0.505840374	0.063127191
107	0.452618	0.069232	0.468995558	0.072470393	0.53393404	0.070958504
108	0.449744	0.0691415	0.45635754	0.068433539	0.35687589	0.066710339
109	0.4472595	0.0690325	0.484405444	0.06259597	0.550400464	0.080851364
110	0.431826	0.069061	0.411194735	0.071715903	0.331510043	0.070066262
111	0.3931745	0.0690925	0.44645351	0.068546324	0.324879995	0.074887236
112	0.3424225	0.0689665	0.395650385	0.070322259	0.393170401	0.062564318
113	0.307174	0.06896	0.345062732	0.070073738	0.406689854	0.058902827
114	0.277947	0.069103	0.23764317	0.074561641	0.328026284	0.073687993
115	0.245018	0.0691905	0.201546091	0.070245393	0.312861854	0.06613796
116	0.214454	0.069163	0.237385243	0.064024435	0.089956408	0.069563486
117	0.185522	0.069186	0.216839527	0.065486006	0.300338796	0.078288421
118	0.1600255	0.069194	0.22116018	0.064807765	0.270571645	0.074823521
119	0.140025	0.069132	0.068571846	0.068852592	0.091282454	0.062375859
120	0.120146	0.069033	-0.068519259	0.063735056	0.226484468	0.073852415
121	0.097245	0.0689575	0.188096636	0.065679027	-0.039313819	0.060199272
122	0.083893	0.068976	0.115537984	0.071488833	0.027276857	0.073161624
123	0.0813425	0.068993	0.073538399	0.071038722	0.162891057	0.07258343
124	0.0790555	0.068976	0.167975551	0.066661843	0.019693757	0.061973917
125	0.077154	0.068944	0.077523361	0.065186111	0.113747222	0.068790939
126	0.0653355	0.069049	0.120505537	0.072909571	0.134550322	0.077500428
127	0.049347	0.069365	0.08001921	0.07048344	-0.012969741	0.073782906
128	0.040694	0.069476	0.01750776	0.070628085	0.073572694	0.068544894
129	0.024817	0.0696355	0.015674329	0.075837276	0.261801892	0.088136019
130	0.00893	0.069894	0.010111545	0.071387776	0.081650667	0.077685598
131	0.005836	0.070153	0.024382404	0.066675427	0.037615353	0.06202643
132	0.0110445	0.070665	0.050090707	0.069074201	-0.010872632	0.079980985
133	0.0128725	0.071809	-0.082457887	0.064029697	0.05738425	0.067958875
134	0.015379	0.073057	-0.037901938	0.0738831	0.088475682	0.065111697
135	0.0196875	0.074434	0.060420011	0.076448297	0.090439231	0.073602894
136	0.025228	0.0761735	0.030050654	0.08293619	0.040694678	0.079037943
137	0.035765	0.077713	-0.017146816	0.069637946	-0.038105587	0.083019053
138	0.0488255	0.0797965	-0.047343275	0.078639878	-0.121267014	0.075459165
139	0.08783	0.083213	0.025371752	0.084004098	0.08272402	0.076694359
140	0.127151	0.085807	0.079077872	0.086890172	0.104189718	0.08444591
141	0.177795	0.0876815	0.18073099	0.08364826	0.355150212	0.090667269
142	0.228523	0.088977	0.119213554	0.093838208	0.116182023	0.096287747
143	0.247204	0.089195	0.289616934	0.092823518	0.121916644	0.084677669
144	0.275947	0.088795	0.224292482	0.08153183	0.308651433	0.086055109
145	0.326797	0.08746	0.277203205	0.085839269	0.388836417	0.095048107
146	0.369096	0.085788	0.339970236	0.08508771	0.323967539	0.075977829
147	0.421201	0.08336	0.496609529	0.083982427	0.264652664	0.090214827
148	0.488269	0.0792815	0.432807645	0.074262062	0.420533595	0.075859536
149	0.528807	0.075638	0.430495951	0.075398068	0.437059606	0.074550827
150	0.572264	0.0716575	0.591227594	0.070341013	0.460019438	0.073925279
151	0.6255685	0.066423	0.648903355	0.066175501	0.847870588	0.063177446
152	0.658261	0.06248	0.770102337	0.060606696	0.653680291	0.063568662
153	0.697461	0.058017	0.641759403	0.058300762	0.574982593	0.048990208
154	0.744108	0.0508265	0.739675113	0.053214495	0.878285548	0.058689709
155	0.759579	0.044803	0.849254176	0.043985257	0.838917456	0.06320978
156	0.766766	0.0387645	0.800178435	0.036996247	0.775137225	0.038346513
157	0.783519	0.0309855	0.791257402	0.032695234	0.869088898	0.031724771
158	0.799591	0.025253	0.838557921	0.022204076	0.749802047	0.028226809
159	0.786765	0.020125	0.775628485	0.01648528	0.756483978	0.024536245
160	0.7602045	0.0146745	0.812427858	0.01571178	0.8043244	0.01696547
161	0.769968	0.011899	0.711142224	0.010341782	0.756491941	0.013543142
162	0.7421215	0.010382	0.723243506	0.006360899	0.545707559	0.003695481
163	0.681616	0.008436	0.616696931	0.008081834	0.731876048	0.013135698
164	0.661829	0.006877	0.671821084	0.001333356	0.69336096	0.006552769
165	0.606337	0.005883	0.673920872	0.00436513	0.489910304	-0.000441617
166	0.5508705	0.004849	0.574558942	0.001203832	0.448381722	-0.005985255
167	0.548296	0.004584	0.510094729	0.000424745	0.567967947	0.015041401
168	0.5120785	0.0047835	0.523723382	0.000748502	0.5314675	0.00803576
169	0.4088	0.0045535	0.320695751	0.003890502	0.360440978	0.01469294
170	0.371329	0.00409	0.435836061	-6.47761E-05	0.482616282	0.005033917
171	0.362013	0.003662	0.332393018	-0.001219181	0.31317607	-0.000414838
172	0.314272	0.0037615	0.310572155	0.004981017	0.288736787	0.004746745
173	0.299017	0.003985	0.324588876	0.002250353	0.260300215	0.010530044
174	0.3023215	0.0037405	0.326642243	0.002112986	0.419601938	-0.001541848
175	0.2716475	0.0037935	0.202830201	0.001627265	0.243291848	0.002433342
176	0.210991	0.004167	0.165092404	0.006717698	0.210050904	0.01366519
177	0.1763455	0.0040975	0.161392422	0.007105208	0.181182392	0.012064907
178	0.1719035	0.003058	0.221215695	0.000782138	0.174515279	0.003876311
179	0.171085	0.002915	0.190546852	-0.000304987	0.198303973	0.00252202
180	0.151651	0.0028955	0.203184234	-0.004558839	0.045993231	0.006703091
181	0.1631805	0.0020055	0.150584519	9.77249E-05	0.120949077	0.007904739
182	0.1686	0.002263	0.122030367	0.006392959	0.188425794	-0.000104106
183	0.1195135	0.002867	0.183263531	0.00323389	0.176172814	0.007478447
184	0.067558	0.002573	-0.028649514	0.010584033	-0.003640855	0.006466842
185	0.055524	0.001942	-0.016200899	0.006624096	0.175320689	0.001518371
186	0.0241085	0.0015125	0.002254821	0.003668691	0.039470073	0.005838711
187	0.036136	0.0012765	0.095518821	0.004254433	-0.088805513	0.006204116
188	0.077674	0.001553	0.120499508	-0.002488999	-0.066998135	-0.000173828
189	0.069413	0.002025	0.067176158	0.002930023	0.18567456	0.006102773
190	0.03137	0.002677	0.050426287	-0.001148923	-0.010437055	0.007332576
191	0.028506	0.003033	0.078032197	0.000311669	0.091862465	0.011539029
192	0.0129315	0.0027295	0.013006639	0.000689772	0.004614191	0.001234809
193	0.0426395	0.002181	-0.00223407	0.000410349	0.164473279	-0.002629795
194	0.081144	0.001485	0.172235652	-0.001152335	-0.02455998	0.000183988
195	0.0842935	0.0008025	0.116974998	-0.000727394	0.137453033	-0.005037722
196	0.0319665	0.000601	-0.017067138	-0.000428295	0.085921785	-0.001889849
197	0.059954	0.000522	0.019115378	-0.00334670	0.178454432	0.005343647
198	0.0476225	0.0002455	0.049644575	0.00320726	-0.197274133	0.006611864
199	0.0375775	0.000624	0.055776155	0.004282928	0.046703188	0.000149339
200	0.020896	0.001023	-0.032764076	-0.002131614	0.134392904	0.004050182
201	0.0082865	0.0009825	0.008690857	0.000141891	0.093829105	0.002878536
202	0.0236855	0.000964	0.014104481	0.000715944	0.116520268	0.007542362
203	0.033514	0.000971	-0.05439871	-0.001636579	0.05882744	0.008683566
204	0.033504	0.000753	0.072285439	0.003689283	0.006591436	0.013367025
205	0.032077	0.000619	-0.020255889	0.001055917	0.15034936	-0.004016634
206	0.028738	0.000856	0.062145349	0.004056244	0.024159869	0.003712108
207	0.0320225	0.0010515	0.046782077	0.000471427	0.031089241	-0.005313497
208	0.0267925	0.001172	-0.018191826	0.002981444	0.011633895	-0.005164091
209	0.017453	0.001302	0.006120766	0.003582415	-0.053724241	-0.005625019
210	0.0172805	0.001457	-0.012457593	-0.000388078	0.040299713	-0.001762801
211	0.0040095	0.00162	0.037335005	0.001664184	0.091730332	0.000976534
212	0.003797	0.001448	0.005956259	0.000231478	0.010089991	0.002006243
213	0.0103015	0.0010485	-0.081990563	-0.000498062	-0.182465716	0.001002416
214	0.013762	0.0009425	0.086990676	-0.004415771	0.073505945	0.000695719
215	0.010491	0.001016	-0.030762779	-0.001094001	0.017693628	0.005099046
216	0.005659	0.0011615	0.056953297	0.005023535	0.137496314	-0.003829194
217	0.007934	0.00132	-0.048948152	0.003623715	0.014334318	0.006089687
218	0.006584	0.001235	-0.055874515	0.004406406	0.09634165	0.001933655
219	0.006306	0.0010075	0.029372534	0.00049552	-0.137190605	0.000146519
220	0.007774	0.0008535	-0.026379421	0.001951439	0.08642382	0.000874531
		RMSE	0.051977511	0.003100968	0.089364677	0.00577409
		MAE	0.042382314	0.002504553	0.071461354	0.004554895



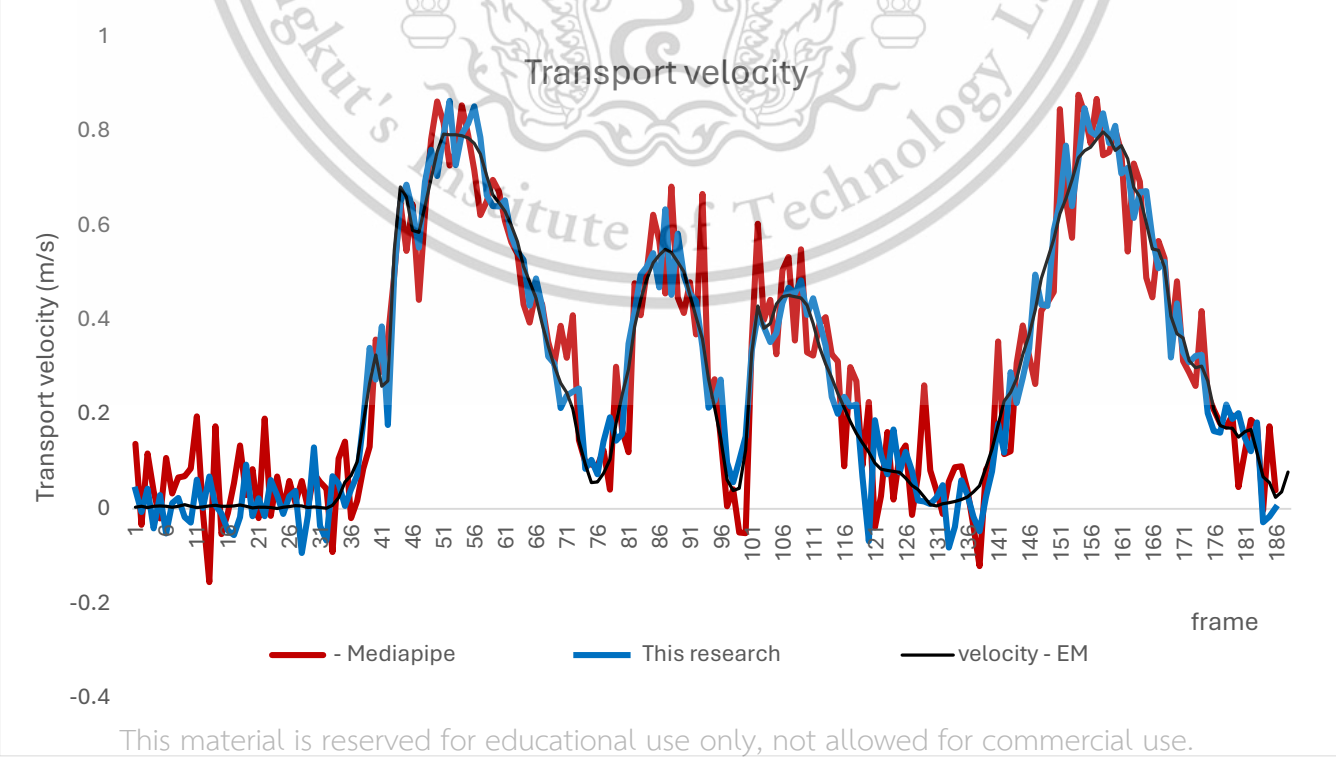
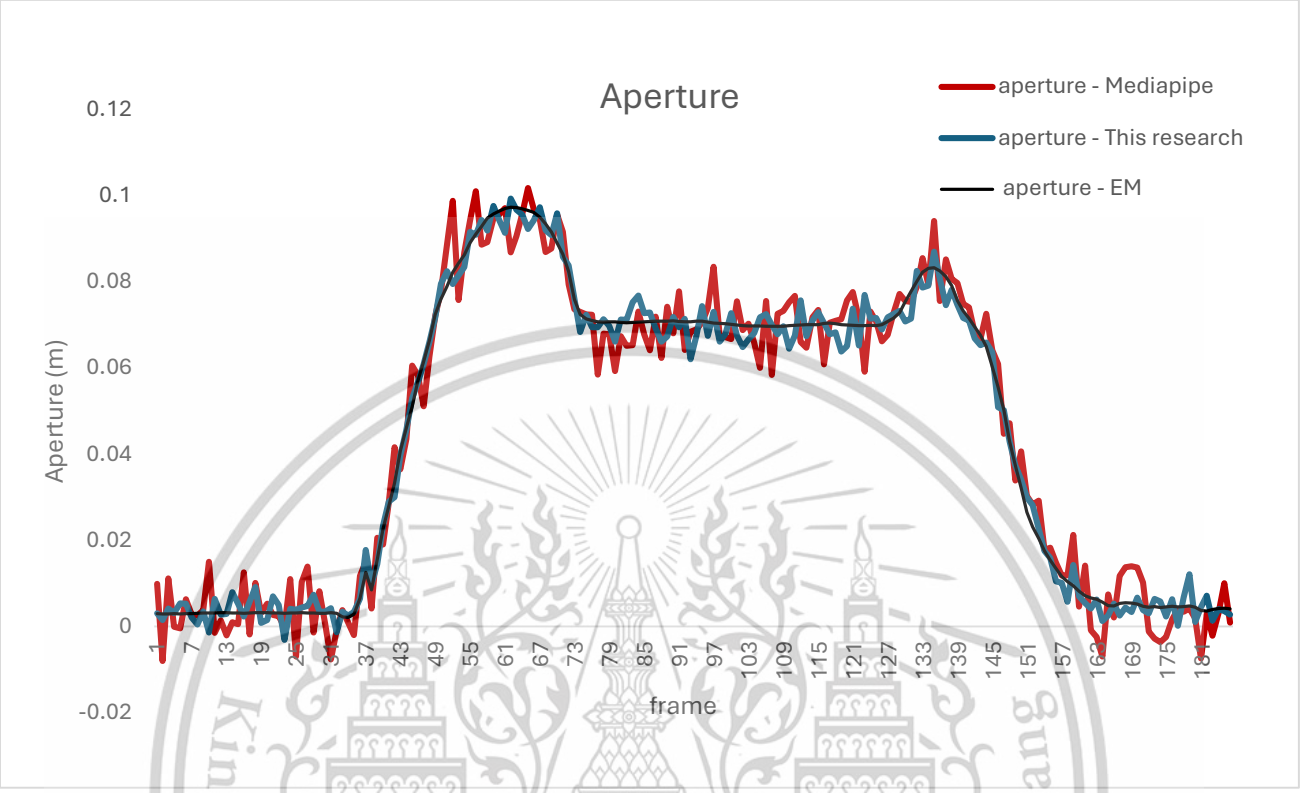


Table 3 Result from trial 3

frame	velocity - EM	aperture - EM	This research	aperture - This research	- Mediapipe	aperture - Mediapipe
1	0.0038525	0.002943	0.041760574	0.003046368	-0.063120603	0.009852337
2	0.003814	0.002914	0.12249821	0.001445011	-0.019947871	-0.007993219
3	0.005187	0.0029095	0.027045787	0.004119948	-0.027585019	0.011145868
4	0.004435	0.00293	0.019011118	0.003079479	0.026246419	-6.36336E-05
5	0.001784	0.002926	0.083735981	0.00531199	0.060859078	-0.000468161
6	0.0031777	0.0029395	-0.01569332	0.005246481	-0.006224806	0.00634327
7	0.003858	0.0029675	0.000672692	0.002050335	-0.047339329	0.002734468
8	0.004004	0.003003	0.019912239	0.000448595	-0.035411942	0.002547138
9	0.003731	0.0030795	0.010990755	0.003469748	0.033758845	0.003816162
10	0.0046685	0.0030965	-0.044485416	-0.001422778	0.033050953	0.015045986
11	0.004584	0.003097	-0.040131285	0.006424177	-0.062189781	-0.001513441
12	0.004707	0.003155	-0.02483128	0.002777922	0.077673684	0.001370435
13	0.004861	0.00316	-0.015464219	0.002898544	-0.100555977	-0.002127647
14	0.004129	0.003098	-0.015621296	0.007933114	-0.154212235	0.00095075
15	0.0045105	0.003079	-0.06248476	0.005242305	-0.048295239	0.000516876
16	0.0070295	0.0030745	-0.022174116	0.002262421	0.00218915	0.012559234
17	0.002655	0.0031	-0.004345042	0.005685758	-0.158345751	-0.001910719
18	0.003506	0.0031885	0.094981499	0.009133634	0.1345677	0.010122839
19	0.002945	0.003225	0.107971439	0.000813913	-0.001385715	0.003089569
20	0.000382	0.003176	-0.018308196	0.001483449	0.032586976	0.005289899
21	0.0009665	0.0031215	0.079639093	0.007011325	0.057489103	0.002661728
22	0.0022615	0.0030765	-0.140479423	0.005008218	-0.021433797	0.002371372
23	0.00309	0.003068	-0.03662775	-0.003101489	0.110829999	-0.000139539
24	0.004091	0.003097	-0.019336901	0.0040723	0.03032758	0.010967905
25	0.0027045	0.00315	0.050526817	0.003822012	-0.053284284	-0.006975428
26	0.006132	0.003164	0.032266567	0.004413344	-0.102355531	0.010343777
27	0.0032655	0.003133	0.005613496	0.004758762	0.053694352	0.013909919
28	0.0030455	0.00308	-0.064964627	0.007389048	-0.104394008	-0.001408724
29	0.007753	0.003025	-0.009377229	0.003410686	0.085749463	0.00814236
30	0.030053	0.0030235	0.04570483	0.003382152	0.012718709	0.000665736
31	0.050401	0.0032025	0.047618114	0.004264262	0.02955014	-0.00766361
32	0.087625	0.003051	0.141220039	-0.001326476	0.042953484	-0.000943532
33	0.1360865	0.0022465	0.084842275	0.003395616	0.11589658	0.003797023
34	0.187242	0.002143	0.180876525	0.002495285	0.229815583	0.000852682
35	0.225372	0.002829	0.215682684	0.003328032	0.297544262	-0.002054289
36	0.2132105	0.0065465	0.206068238	0.006495794	0.241284093	0.011730894
37	0.196419	0.01259	0.174252362	0.017800561	0.117674505	0.015005327
38	0.164995	0.008502	0.166754062	0.009820773	0.150842162	0.004128012
39	0.283755	0.015582	0.273752666	0.01452776	0.337110096	0.020627481
40	0.5104625	0.0227225	0.50327704	0.023439386	0.507143496	0.019032556
41	0.551701	0.027949	0.500829387	0.029023187	0.495061776	0.028780163
42	0.5786315	0.033326	0.568811282	0.03002652	0.526488967	0.04169529
43	0.577543	0.0408035	0.505810024	0.039715135	0.571714934	0.036524438
44	0.593316	0.046244	0.508271899	0.045782195	0.636482933	0.043601304
45	0.6592155	0.05109	0.598482463	0.053088268	0.618425879	0.06063693
46	0.7543445	0.0571545	0.806127653	0.056743437	0.722752011	0.058420065
47	0.783503	0.061608	0.7722135	0.061046616	0.7259127	0.051175842
48	0.7690345	0.0665385	0.794275434	0.066135973	0.753271383	0.062842405
49	0.7491285	0.0725215	0.697341462	0.071813108	0.727852262	0.072218854
50	0.730054	0.076106	0.766310681	0.07971232	0.836397961	0.077998006
51	0.722116	0.0790915	0.718473205	0.08260933	0.683846942	0.088884349
52	0.733918	0.0823775	0.735193467	0.07961152	0.70502801	0.0989694
53	0.713311	0.084463	0.71749718	0.081637826	0.742183299	0.075932498
54	0.6779505	0.086399	0.70037196	0.083556861	0.757372591	0.086988757
55	0.6468765	0.089212	0.638073116	0.091794537	0.669227239	0.094418501
56	0.633556	0.091277	0.650729176	0.091107934	0.641246548	0.101230246
57	0.607594	0.093022	0.617286444	0.094507443	0.563938411	0.0888019
58	0.565567	0.094927	0.550987017	0.09209584	0.684855398	0.089403669
59	0.529481	0.095951	0.558960329	0.097775419	0.565885155	0.094862789
60	0.5009885	0.0966165	0.575150798	0.094547466	0.457595874	0.095775144
61	0.4690345	0.0972155	0.439236385	0.091563924	0.54953128	0.097289441
62	0.442866	0.097474	0.442115145	0.099567393	0.3558428	0.08696529
63	0.4165845	0.097488	0.355021129	0.096902358	0.602164972	0.090759631
64	0.362518	0.097121	0.370074401	0.0957516	0.310593004	0.0959223
65	0.321984	0.096737	0.28384537	0.092458151	0.340558251	0.102005746
66	0.2920475	0.0963115	0.32217343	0.094474615	0.311804073	0.097029495
67	0.264671	0.095174	0.333069216	0.097462994	0.267444645	0.09458476
68	0.250589	0.09364	0.219052202	0.09212309	0.3040105	0.08707773
69	0.223497	0.0917575	0.205654866	0.091052749	0.129422459	0.087913289
70	0.18414	0.08915	0.19117591	0.096086991	0.401924362	0.095768147
71	0.16358	0.086563	0.148411554	0.085991783	0.160687547	0.091754323
72	0.1470435	0.082529	0.062451108	0.083915376	0.204537519	0.079546636
73	0.1240985	0.0760595	0.094149443	0.07618605	0.119874533	0.073755747
74	0.102899	0.072561	0.111364008	0.068470459	0.176363446	0.073175138
75	0.077056	0.071547	0.130410858	0.072469393	0.16884478	0.072562721
76	0.0816705	0.071107	0.028269571	0.069555157	0.061901698	0.07247756
77	0.113074	0.070861	0.130411326	0.069550104	0.12634481	0.058587746
78	0.1579755	0.0707785	0.200445442	0.071437539	0.115259907	0.068103594
79	0.2396945	0.070814	0.188648491	0.069849408	0.183958571	0.067907794
80	0.281588	0.070863	0.305282887	0.066248864	0.260750692	0.059402624
81	0.316141	0.070703	0.206900639	0.071338424	0.345863197	0.06751076
82	0.390617	0.070655	0.321003172	0.071260583	0.446838659	0.065251841
83	0.444741	0.070727	0.385976945	0.075416283	0.462245284	0.065400349
84	0.46664	0.0708055	0.450245605	0.076924142	0.390725314	0.073235372
85	0.4826025	0.0708565	0.380999436	0.072828108	0.487375598	0.067919178
86	0.481802	0.070891	0.419980964	0.073004726	0.407307189	0.064214071
87	0.465756	0.0709785	0.369932992	0.069320006	0.52551168	0.072012798
88	0.413689	0.0710065	0.482255553	0.066201294	0.29626494	0.062413852
89	0.363899	0.070992	0.343127718	0.067434423	0.352209394	0.074330478
90	0.329113	0.071043	0.324995638	0.071930729	0.27101475	0.068132833
91	0.257894	0.070955	0.205788383	0.069579814	0.255705769	0.077883563
92	0.183859	0.070866	0.185423327	0.071499052	0.144603921	0.064325284
93	0.1118505	0.070879	0.056145593	0.062131642	0.19716047	0.068543255
94	0.032388	0.0709785	0.048156595	0.067471421	0.112445101	0.069040815
95	0.01196	0.071	0.110852191	0.074514942	-0.009492972	0.070720519
96	0.016925	0.070802	-0.036154874	0.067604452	-0.046346378	0.074047304
97	0.1303265	0.0705205	0.158987496	0.07312267	0.170788606	0.083685178
98	0.32565	0.070442	0.396602355	0.06624699	0.361313131	0.067499541
99	0.3647515	0.070382	0.395910552	0.068033138	0.371606969	0.067281252
100	0.3245425	0.070223	0.306093279	0.07287749	0.284946075	0.066855198
101	0.347496	0.070086	0.327256454	0.067611526	0.421794816	0.075627865
102	0.3749385	0.069973	0.434841469	0.064962145	0.251389081	0.068886568
103	0.3888355	0.0698615	0.382861954	0.066779161	0.291646766	0.070401571
104	0.391389	0.069887	0.36366108	0.068237971	0.308149141	0.065961616
105	0.386301	0.0698555	0.360524379	0.071887071	0.441278094	0.060144565
106	0.37432	0.069793	0.399699675	0.072657893	0.28732874	0.075649939
107	0.353737	0.06982	0.42507442	0.070136215	0.486913754	0.058518445
108	0.3316905	0.0698275	0.325876549	0.067974791	0.242994726	0.072692131
109	0.3050355	0.069836	0.314656887	0.069768827	0.426684987	0.073396946
110	0.286323	0.06992	0.329207536	0.064591997	0.378931379	0.075394915
111	0.26082	0.0700005	0.273051495	0.067660043	0.332153853	0.076904684
112	0.23133	0.0700965	0.208384548	0.075862925	0.096287153	0.066158714
113	0.21505	0.070185	0.233594437	0.067499523	0.211908297	0.064821641
114	0.18773	0.070194	0.153647665	0.071149751	0.146162217	0.07190043
115	0.13835	0.0701865	0.045770444	0.073103663	0.105384381	0.07362255
116	0.092245	0.07049	0.141722434	0.070520301	0.093149101	0.060938995
117	0.0453705	0.0705635	0.044213258	0.067957264	-0.025868572	0.070634968
118	0.0180485	0.070372	0.131259628	0.068411396	0.075722113	0.071074613
119	0.02286	0.070213	-0.006107926	0.06395656	-0.09293286	0.071443995
120	0.027107	0.070093	0.064977137	0.065160307	-0.027874021	0.075865103
121	0.041374	0.070031	0.098197671	0.073912117	0.091058062	0.077742351
122	0.056082	0.069925	0.006805796	0.065358797	0.110484531	0.071637807
123	0.0524765	0.0699585	0.019251341	0.077127247	0.021205463	0.059222021
124	0.030552	0.0700165	0.087459608	0.071570001	-0.032852809	0.073263741
125	0.018131	0.069937	-0.035403245	0.071715233	-0.144859135	0.070943147
126	0.0223645	0.070167	0.00445401	0.069073992	-0.014882536	0.066272531
127	0.0413665	0.0709	-0.029408426	0.071910412	0.162330812	0.067800146
128	0.054195	0.07168	-0.006967944	0.0726006	0.051061646	0.072748687
129	0.0698635	0.072944	0.067733855	0.073392999	0.081109269	0.077356666
130	0.0904335	0.0755475	0.028542265	0.070935695	0.128287899	0.075678887
131	0.122565	0.077929	0.133857788	0.071586915	0.096177227	0.075481052
132	0.1774155	0.0802245	0.161120357	0.082683465	0.175329655	0.078937731
133	0.248598	0.0823935	0.215104337	0.078788788	0.355991096	0.085638443
134	0.291479	0.083261	0.244774883	0.079261561	0.223613308	0.079464134
135	0.3351425	0.0834435	0.358870531	0.087121981	0.392800413	0.094282767
136	0.4039885	0.0826635	0.373009089	0.080887563	0.29820683	0.07567852
137	0.461467	0.081319	0.368488197	0.074748978	0.611526296	0.085362201
138	0.521045	0.079224	0.466438565	0.078293831	0.477228879	0.080800593
139	0.6077815	0.075776	0.602980743	0.074762298	0.533842513	0.079878919
140	0.660152	0.073408	0.667997667	0.071771141	0.684686092	0.075003514
141	0.7001525	0.0716735	0.666731577	0.071179675	0.64121449	0.074188687
142	0.751876	0.0696455	0.749153007	0.066954203	0.850772074	0.06828098
143	0.784597	0.067749	0.838151584	0.065381168	0.734075379	0.066922529
144	0.809047	0.065109	0.893974691	0.065996912	0.806759018	0.072675883
145	0.822834	0.0603595	0.831220357	0.063699914	0.812047566	0.064243436
146	0.821888	0.055658	0.886891303	0.05100359	0.790300987	0.061042531
147	0.8119345	0.050374	0.776318806	0.050273048	0.770896876	0.044831563
148	0.807106	0.043027	0.849545028	0.043035648	0.825095954	0.047271908
149	0.80163	0.037432	0.838573828	0.03746056	0.738481811	0.033951548
150	0.771653	0.0322245	0.748574238	0.034182206	0.777530938	0.040705699
151	0.746908	0.026537	0.750778015	0.029957583	0.765618302	0.030332802
152	0.730736	0.023139	0.70731538	0.028163581	0.614679164	0.028349587
153	0.674841	0.020448	0.645108383	0.022666384	0.881320119	0.029240148
154	0.619348	0.0175565	0.638349264	0.017541471	0.633620188	0.017795995
155	0.591177	0.015386	0.60282773	0.015925913	0.534269065	0.018324451
156	0.5544955	0.013433	0.537616505	0.010503303	0.679406709	0.014829965
157	0.498671	0.011587	0.470928209	0.010133371	0.464166988	0.011856844
158	0.464394	0.010383	0.374640674	0.005724218	0.58299264	0.01190546
159	0.4260685	0.009471	0.452282188	0.014298709	0.479585361	0.021301302
160	0.3811355	0.008208	0.30306808	0.007014061	0.417514919	0.004608333
161	0.360821	0.00716	0.319647364	0.005415812	0.303298458	0.014121768
162	0.324456	0.006617	0.234075958	0.004190292	0.365456086	-0.000890365
163	0.3077715	0.0062905	0.297020564	0.006232193	0.398687061	-0.002486507
164	0.271895	0.005663	0.322559535	0.001255448	0.323352471	-0.007040006
165	0.2075115	0.0048365	0.158669133	0.002492866	0.243035114	0.007438011
166	0.197442	0.004761	0.177277131	0.005282355	0.257664313	0.002069153
167	0.185849	0.00536	0.071662175	0.002527395	0.347381154	0.011738671
168	0.120609	0.005475	0.171269819	0.004376083	0.193009667	0.013748208
169	0.0824565	0.005412	0.072396767	0.003317444	0.018150111	0.013975961
170	0.063608	0.005171	0.05139199	0.006673305	-0.054433632	0.013709545
171	0.067946	0.004705	0.091703514	0.003757838	0.051852003	0.010213731
172	0.181548	0.004465	0.09214282	0.003017542	0.135323171	-0.001199724
173	0.191683	0.004602	0.093163257	0.006411654	0.011830213	-0.002869705
174	0.097012	0.004394	0.06663761	0.005776613	-0.033165699	-0.003647115
175	0.0278565	0.0045215	0.024342552	0.002276049	0.096783528	-0.002437667
176	0.03704	0.004681	0.096786873	0.006304746	-0.003545648	0.001598885
177	0.028117	0.0045145	-0.017174588	0.000154356	0.127633264	0.003999228
178	0.0200175	0.004625	-0.01480979	0.006753622	0.052153161	0.003378573
179	0.031658	0.004782	0.060820035	0.012135058	-0.090929664	0.004174689
180	0.0299425	0.004428	0.024727898	0.001044064	0.005118445	0.001830878
181	0.0333445	0.003735	0.019479746	0.004469889	0.062889666	-0.007451363
182	0.015875	0.003587	0.088690532	0.007104921	0.137966222	0.002910566
183	0.0146815	0.003917	-0.071119076	0.001318843	-0.01803434	-0.002204603
184	0.015292	0.004189	0.10162001	0.00403065	-0.145712165	0.003102673
185	0.007795	0.004203	0.083200545	0.003595194	-0.050550453	0.010045388
186	0.0117045	0.00409	0.065092309	0.002743192	0.03985861	0.000894791
187	0.018263	0.0038975	0.029629801	0.006804738	0.043090734	-0.004808853
188	0.013703	0.003635	0.117237886	0.007126191	0.008819132	0.007498897
189	0.01932	0.0034835	0.0329309	0.003689282	-0.051947051	0.005077166
190	0.0213065	0.0036125	0.077615435	0.007023012	-0.04852299	0.002973803
191	0.018079	0.003385	-0.130783292	0.001143642	0.028756333	0.001565652
192	0.0216255	0.003162	-0.009076993	0.008468516	0.123151068	0.003709179
193	0.0178535	0.0033315	0.07807541	0.009852033	-0.005003736	0.010511265
194	0.01645	0.003384	0.018279628	-0.000295825	0.026347124	-0.003508052
195	0.029307	0.00332	0.008501582	-0.00114483	-0.099736509	6.9729E-06
196	0.018724	0.003704	0.018515454	0.007454563	0.019114718	0.01314355
197	0.008606	0.00401	0.067275637	0.004382531	0.116018541	0.004034058
198	0.0117895	0.0038755	0.1172135	0.006646098	0.031857357	0.003464593
199	0.0125485	0.003678	-0.02637063	0.004268804	0.005339726	0.00534933
200	0.009595	0.00365	-0.039076991	0.005719835	0.037951587	0.002668509
201	0.0074425	0.0036485	-0.026545551	0.004380071	0.125207326	-0.002981048
202	0.0084165	0.00369	-0.003509233	0.006087037	-0.070784212	0.002104592
203	0.008204	0.003632	0.117357778	0.004706595	-0.20513429	0.002027905
204	0.006605	0.0033505	-0.01927754	0.002198553	0.059614581	-3.57471E-05
205	0.00588	0.003074	0.020919991	0.002833856	0.052693867	-0.000548288
206						
207		RMSE	0.050155622	0.002958631	0.074345821	0.005576853
208		MAE	0.039535937	0.002354267	0.059317628	0.004456743



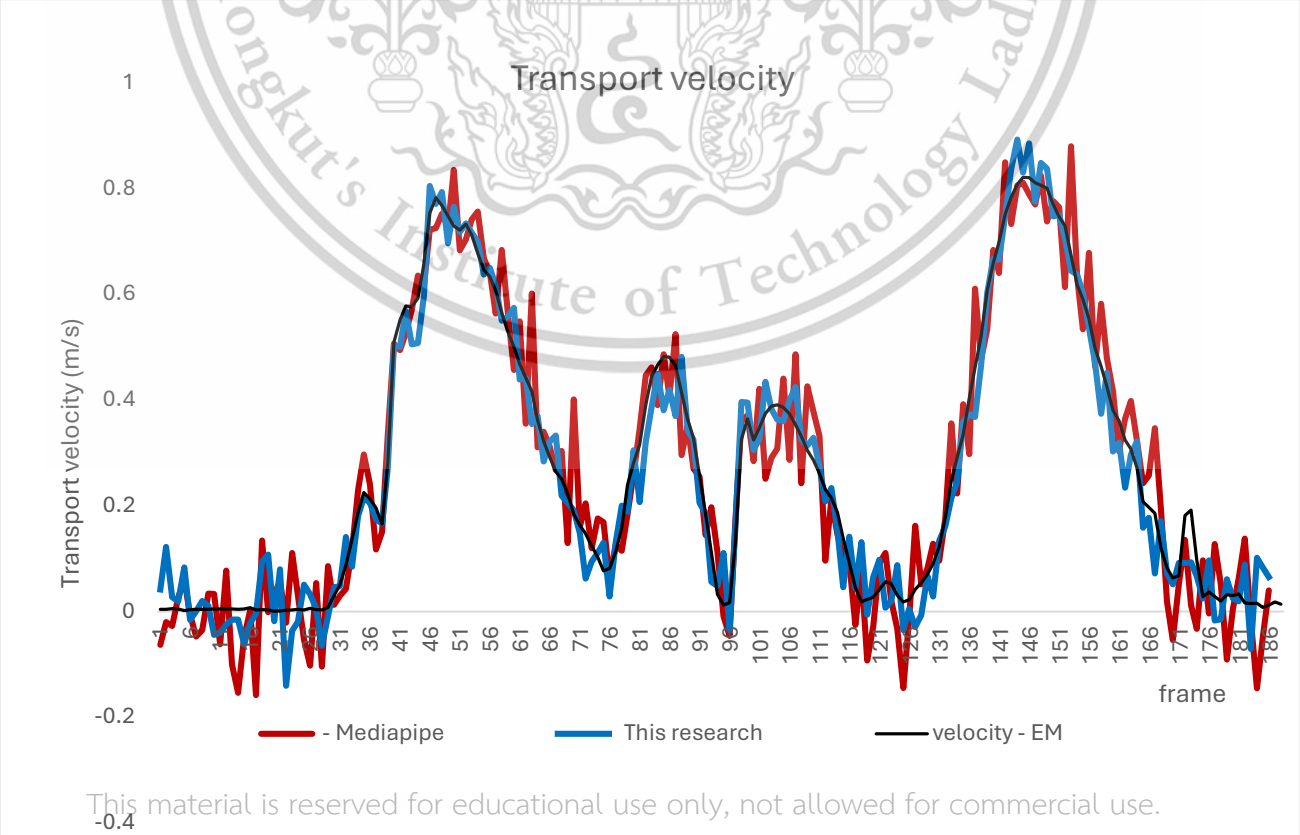
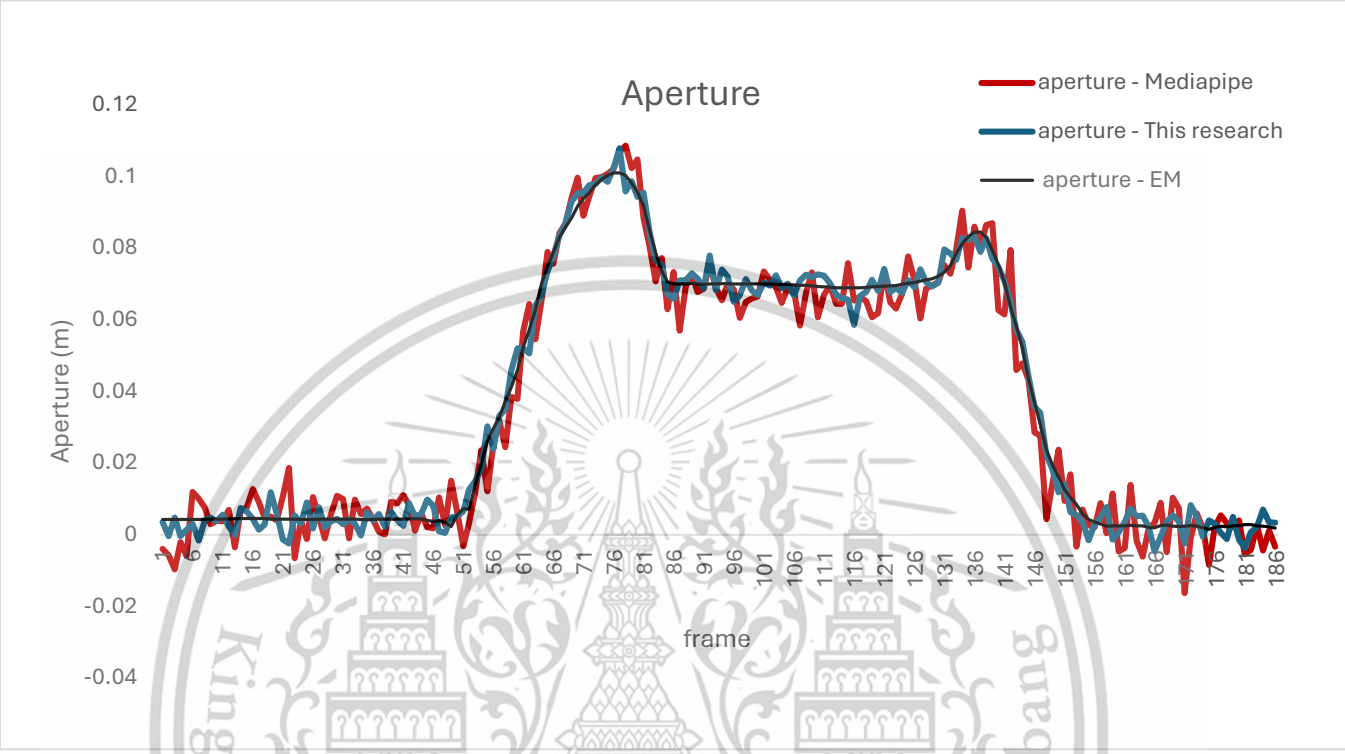


Table 4 Result from trial4

frame	velocity - EM	aperture - EM	This research	aperture - This research	- Mediapipe	aperture - Mediapipe
1	0.0012895	0.004273	-0.064205476	0.003521921	0.071532986	-0.004040171
2	0.003771	0.004238	0.04433661	-0.000415715	0.012560125	-0.005766794
3	0.0055285	0.004208	-0.038082795	0.004759206	0.040033297	-0.00976067
4	0.0044285	0.004206	-0.035866789	-0.000377156	-0.034120669	-0.002135
5	0.005901	0.00421	0.024125053	0.001406899	0.069015538	-0.005983284
6	0.0032275	0.004206	0.056458964	0.003006824	0.127673873	0.011947114
7	0.003715	0.004204	0.040940467	-0.001656116	-0.043202629	0.010015199
8	0.004634	0.00423	0.098881338	0.003978515	0.11532372	0.007567554
9	0.0052195	0.004285	0.022757168	0.004713534	0.095535361	0.00292624
10	0.002246	0.00433	-0.005483282	0.003804309	-0.106836592	0.003895163
11	0.004229	0.00435	0.064812855	0.00561404	0.119925901	0.003686111
12	0.006197	0.004375	0.019679037	0.002230066	-0.044569971	0.006874405
13	0.006054	0.0044265	0.018917165	-2.65859E-05	-0.044552713	-0.003512967
14	0.004612	0.004484	0.062802469	0.007416163	-0.109164048	0.006762479
15	0.0042525	0.0045	0.02448833	0.006440286	-0.042985864	0.007560928
16	0.0034285	0.0045005	0.037132979	0.004390631	0.069496787	0.01271465
17	0.005636	0.004508	0.000762753	0.001408174	0.004609105	0.009041235
18	0.0063295	0.004474	-0.037861455	0.002793977	0.089117468	0.004747327
19	0.0039365	0.0043555	-0.023487679	0.01187966	0.004668972	0.005030621
20	0.00373	0.00432	-0.100259964	0.005801185	-0.157397608	0.003980899
21	0.0060835	0.004328	0.03791402	-0.001411345	0.006268448	0.010698737
22	0.010569	0.004337	-0.108245888	-0.002495631	0.010891579	0.018635368
23	0.006701	0.004331	0.059505628	0.005370422	-0.007535721	-0.006587158
24	0.003372	0.004267	0.042377067	0.003109346	0.0641615	0.003928163
25	0.004819	0.0042095	-0.038571111	0.00898923	-0.120793238	-0.001267128
26	0.002332	0.004256	-0.007840715	0.001701748	0.033594155	0.010525101
27	0.0034975	0.0042935	0.014135953	0.007630859	-0.142184301	0.004767369
28	0.005067	0.004315	-0.023837864	0.001959926	-0.059521227	-0.001017014
29	0.006606	0.0043	0.004057163	0.00373518	0.002792212	0.005536997
30	0.00517	0.004279	0.035591114	0.004372202	0.02227874	0.010815334
31	0.003582	0.004313	0.03626465	0.00292775	-0.002627026	0.009931759
32	0.001636	0.004352	0.050037147	0.004332859	-0.095803543	-0.001005917
33	0.000407	0.0043485	-0.014964986	0.003043585	-0.125665628	0.009786881
34	0.0003975	0.0042245	-0.004620291	-0.000231995	0.025333956	0.005729455
35	0.001835	0.004153	0.104634781	0.006294355	0.025325272	0.00729122
36	0.0047935	0.0042285	-0.076030089	0.00400787	0.012785114	0.004158535
37	0.0048605	0.0042975	0.131152594	0.005749556	-0.052815486	0.000871243
38	0.003892	0.004293	-0.030800058	0.002146139	-0.039078463	4.31208E-05
39	0.0043835	0.0042915	-0.067066589	0.006386163	-0.093599182	0.009174684
40	0.004091	0.0043065	-0.044599048	0.004068218	0.070409182	0.008699745
41	0.005301	0.004329	0.004723114	0.002476617	-0.156780884	0.011059899
42	0.0053035	0.0043685	0.037321959	0.00880794	-0.088083499	0.008399779
43	0.0125725	0.0044265	-0.011677929	0.005136272	0.02865983	0.00110159
44	0.038054	0.004392	-0.065974029	0.005677623	0.096592213	0.00591855
45	0.0645945	0.0039485	0.094044453	0.009807008	-0.032015396	0.002067089
46	0.146074	0.0036875	0.156365982	0.008087595	0.114197005	0.001710092
47	0.223122	0.00398	0.18881349	0.000893213	0.273159756	0.010407534
48	0.2177285	0.003354	0.119877721	0.000508474	0.187535449	0.002577586
49	0.226862	0.0022805	0.127555453	0.004793517	0.122475767	0.015019664
50	0.292654	0.005448	0.386422622	0.005155788	0.310500285	0.006241782
51	0.2579145	0.007315	0.258327951	0.006522871	0.158413636	-0.00332905
52	0.1723675	0.007136	0.16461375	0.012671006	0.271638967	0.003297902
53	0.314994	0.013933	0.326792108	0.014954323	0.233482495	0.011797003
54	0.481227	0.019811	0.418922484	0.01837612	0.415449645	0.023599394
55	0.509117	0.026179	0.471141061	0.030249101	0.636475734	0.012092871
56	0.525284	0.029769	0.632362009	0.023958023	0.539261589	0.02525282
57	0.558511	0.03279	0.563978506	0.033163987	0.527517192	0.031863059
58	0.5705575	0.0372915	0.632391928	0.034972797	0.543891206	0.024468516
59	0.628239	0.041297	0.631906201	0.045924697	0.57497824	0.038519399
60	0.689476	0.0459725	0.712440129	0.052144303	0.716036741	0.037925312
61	0.7526205	0.052404	0.75979546	0.052098527	0.825501316	0.056830496
62	0.781927	0.057303	0.840287836	0.050651332	0.694147536	0.06444588
63	0.766962	0.062829	0.747509301	0.064071256	0.816840081	0.054572818
64	0.7533175	0.0700885	0.697688338	0.066750621	0.800436605	0.065269547
65	0.753672	0.074932	0.741470374	0.073707843	0.709082913	0.079037431
66	0.75593	0.078874	0.774885392	0.077891511	0.742424561	0.075767305
67	0.7516115	0.0831895	0.764831775	0.083633996	0.601594454	0.084271128
68	0.750095	0.085964	0.705001992	0.086950084	0.894444085	0.086971656
69	0.7164035	0.0885175	0.691283362	0.093112514	0.749979217	0.094087851
70	0.653339	0.091824	0.691576811	0.095407592	0.675134307	0.099767134
71	0.636779	0.093997	0.681163771	0.095620953	0.613543695	0.089127405
72	0.622983	0.095714	0.597942011	0.09776554	0.646878974	0.09473672
73	0.581324	0.097856	0.568675661	0.09799273	0.494921896	0.099740564
74	0.544554	0.099375	0.552803614	0.099923271	0.579990892	0.100016626
75	0.5085225	0.1004315	0.549042604	0.098608778	0.43906881	0.100863318
76	0.457381	0.101188	0.420545007	0.102439182	0.346162302	0.102193932
77	0.419026	0.101183	0.387748046	0.108114932	0.386304659	0.106844821
78	0.38427	0.100419	0.415072768	0.095970674	0.384108159	0.108812098
79	0.3438185	0.0982855	0.330999609	0.098834052	0.390271765	0.102469664
80	0.311104	0.095743	0.266001244	0.094456589	0.266705599	0.104895583
81	0.281357	0.0919715	0.321862442	0.095597166	0.133339099	0.088569884
82	0.2352875	0.0850575	0.271494954	0.084599808	0.148040536	0.080534658
83	0.189974	0.078761	0.147163401	0.076612503	0.241987252	0.070777161
84	0.1255685	0.0736285	0.27037941	0.075500229	0.107361101	0.07734151
85	0.0618095	0.0706325	-0.018910329	0.067227559	0.06905641	0.06301595
86	0.066353	0.0701	0.123240369	0.065961899	0.114604705	0.073404257
87	0.104261	0.0700635	0.176200122	0.071064462	0.122881949	0.057056419
88	0.173286	0.0701885	0.153353176	0.071170245	0.121364696	0.069485433
89	0.234656	0.070229	0.172140619	0.073014002	0.16102755	0.072795897
90	0.2874565	0.070058	0.248890787	0.071590958	0.263205482	0.067879805
91	0.3517135	0.070001	0.346515017	0.068852247	0.320822672	0.06878821
92	0.398192	0.070081	0.340376114	0.078087546	0.301456031	0.075913123
93	0.4238555	0.0701265	0.488792618	0.068380917	0.470620659	0.069025006
94	0.4434165	0.070215	0.310809627	0.074128191	0.38245611	0.065499819
95	0.435786	0.070216	0.400246003	0.072178315	0.357373008	0.070053595
96	0.4039615	0.070131	0.406715348	0.065076343	0.441863886	0.068576059
97	0.3596885	0.070136	0.369506607	0.066971415	0.314281693	0.060624055
98	0.321225	0.070124	0.349402339	0.071422694	0.317471215	0.065120295
99	0.2653505	0.0700535	0.289070728	0.068255457	0.157895873	0.066107236
100	0.1861475	0.070051	0.168231783	0.066944375	0.098832441	0.066611636
101	0.126172	0.070114	0.208646254	0.07040507	0.208417954	0.07357716
102	0.0677345	0.0701345	0.0530915	0.069651755	0.207039918	0.071257211
103	0.0237555	0.070042	-0.0090606	0.072499134	0.106304316	0.069089086
104	0.019526	0.069957	0.029503994	0.068889415	0.11453563	0.06482743
105	0.062573	0.0699015	-0.013254739	0.070177558	0.126119839	0.069114511
106	0.25578	0.0698075	0.25328859	0.066870334	0.31497119	0.068135135
107	0.339366	0.06977	0.315243676	0.071072867	0.288503747	0.058479119
108	0.3142595	0.0697405	0.336046087	0.072687711	0.298762477	0.067699336
109	0.3207295	0.069535	0.324989587	0.071953954	0.276439593	0.073358587
110	0.34622	0.069374	0.2976983	0.07280806	0.260474622	0.060805923
111	0.356443	0.069255	0.385068117	0.072392438	0.363919685	0.067066822
112	0.358779	0.069159	0.335249553	0.070284202	0.287288216	0.069686866
113	0.35813	0.069043	0.281261148	0.067106484	0.448714813	0.064516709
114	0.332362	0.0689825	0.254569782	0.066132831	0.282899346	0.064583463
115	0.299208	0.068975	0.333257581	0.065682773	0.264091535	0.075918534
116	0.28877	0.06899	0.318198002	0.058662544	0.247712099	0.065414868
117	0.2579605	0.069038	0.250782517	0.066808829	0.406460805	0.066517684
118	0.208236	0.069132	0.203994424	0.067864553	0.079783388	0.065293253
119	0.187885	0.069257	0.185166644	0.071262513	0.190221845	0.060742571
120	0.1630905	0.069377	0.176809746	0.068141301	0.313860972	0.061917306
121	0.132448	0.0694765	0.095615781	0.074323504	0.161223746	0.073842337
122	0.115471	0.069516	0.12030136	0.067781113	0.179115623	0.065008086
123	0.0985595	0.0696365	0.027611642	0.068980647	0.279726673	0.063213475
124	0.0831115	0.0700115	0.050009894	0.067608649	0.113146056	0.067319166
125	0.065866	0.070286	0.1073022	0.071168079	0.15618184	0.077824568
126	0.055545	0.0704285	-0.031924188	0.069163753	-0.045960746	0.071471061
127	0.054647	0.0709165	0.113202626	0.074191533	0.086958941	0.060426197
128	0.038492	0.0713	0.040593677	0.070633111	-0.076256721	0.068873307
129	0.0184845	0.071542	-0.034671382	0.069357037	0.085771986	0.069730205
130	0.0181205	0.072284	0.047030257	0.0704379	0.060081399	0.070569535
131	0.027117	0.07341	0.027079319	0.079792622	0.141869765	0.075330942
132	0.063817	0.075224	0.066665125	0.078629749	0.043352779	0.072918943
133	0.1570205	0.078639	0.046826567	0.076760305	0.132896095	0.079680917
134	0.235968	0.081391	0.300122269	0.082847588	0.17856611	0.090564436
135	0.2873265	0.083378	0.331146907	0.082551321	0.119876347	0.074623386
136	0.3477945	0.084632	0.319668895	0.08337267	0.35456754	0.086095949
137	0.408001	0.084554	0.344560606	0.07905298	0.405340431	0.080755788
138	0.4800635	0.083164	0.507463636	0.082908783	0.414066144	0.086550356
139	0.546692	0.0794505	0.501413524	0.077151529	0.590579398	0.087084546
140	0.588296	0.075483	0.464558236	0.074854465	0.581601848	0.062761672
141	0.6505865	0.070605	0.7491777	0.070905399	0.77760559	0.061547597
142	0.722641	0.0636875	0.785606148	0.064898811	0.810938834	0.079551274
143	0.757189	0.058293	0.76319707	0.057228816	0.905334988	0.04602539
144	0.7869305	0.0522555	0.818919285	0.05393289	0.824297826	0.047865637
145	0.8256885	0.043545	0.754628169	0.044296098	0.845567425	0.043271118
146	0.854715	0.036936	0.83941968	0.035759727	0.783102967	0.028547197
147	0.866609	0.0307905	0.867454638	0.034007772	0.943916978	0.027661444
148	0.851025	0.0236975	0.871798512	0.022200472	0.917518796	0.0043192
149	0.84195	0.019411	0.853527654	0.018304975	0.989618563	0.014327005
150	0.8255445	0.0161105	0.732076267	0.011863285	0.890480202	0.023695405
151	0.8083485	0.0125515	0.73268568	0.014063577	0.862049893	0.00942439
152	0.803636	0.010409	0.822013809	0.006271024	0.818078129	0.016891003
153	0.7655585	0.008431	0.77917899	0.005476701	0.628899759	-0.003345748
154	0.7053945	0.005806	0.789080822	0.003526707	0.688891328	0.007003785
155	0.705771	0.00423	0.694797011	-0.00154666	0.69095646	0.002656587
156	0.671425	0.0034745	0.69241253	0.002948024	0.522042904	0.002046264
157	0.5629785	0.0029825	0.557374095	0.004861117	0.515374611	0.00877574
158	0.51845	0.002347	0.526102985	0.007689151	0.537781103	0.000354282
159	0.511198	0.0024085	0.564219371	-0.001429772	0.549173985	0.011500533
160	0.510206	0.0024035	0.498669667	0.000662086	0.434729861	-0.004694597
161	0.429583	0.002413	0.377474652	0.003630106	0.526069571	-0.003749838
162	0.3455305	0.002629	0.364723797	0.007291043	0.340933058	0.013869126
163	0.2909495	0.0024515	0.257488323	0.00516011	0.388557076	-0.00178776
164	0.278382	0.002418	0.241780035	0.005289379	0.238837038	-0.006170867
165	0.296218	0.0020345	0.354998281	0.002096881	0.355825103	0.001898169
166	0.22822	0.001886	0.246012737	-0.004547277	0.279163635	0.003209368
167	0.132464	0.002547	0.195089936	-0.000620177	0.067162814	0.008857316
168	0.089993	0.0027405	0.106803931	0.003582336	0.044417291	-0.004925913
169	0.065202	0.0023615	0.07631006	0.00538146	0.029886719	0.010308431
170	0.09232	0.002289	0.112476454	0.003698972	0.08780251	0.007344843
171	0.1457485	0.002336	0.114982538	-0.002470019	0.078776129	-0.016328825
172	0.109309	0.002553	0.090339519	0.008234165	0.171174627	-0.000957575
173	0.052001	0.002339	0.05733224	0.005047352	0.021055916	0.005970266
174	0.0324255	0.001866	0.026864634	-0.000630905	0.053799079	0.001846881
175	0.0962095	0.001512	0.129845027	0.00392387	0.244573081	-0.008458494
176	0.125754	0.00198	0.109431324	0.003028501	0.173050858	0.0020479
177	0.097665	0.0023705	0.015445021	0.00048323	0.163711185	0.005400379
178	0.021379	0.002192	0.1228705	-0.001246651	0.011996998	0.003152651
179	0.025607	0.002411	-0.038209947	0.004989068	-0.020047726	0.002072993
180	0.02189	0.0025075	0.07004237	-0.001396727	0.058355716	0.003995509
181	0.047723	0.0028175	0.0674842	-0.003692348	-0.004136111	-0.005554202
182	0.073898	0.002796	0.087539799	0.000693027	0.089801214	-0.004276772
183	0.044964	0.0024535	-0.065428823	0.002142937	0.196511946	0.002560004
184	0.02728	0.002329	0.021504154	0.007009627	0.055173431	-0.00446576
185	0.009439	0.002137	0.027064419	0.00344666	-0.14158976	0.00108528
186	0.0229075	0.001778	0.051036972	0.00332684	0.060531779	-0.003415416
187	0.010647	0.0017655	-0.047059953	0.006137294	0.051028833	0.012392255
188	0.013822	0.001866	-0.054468782	0.003099284	0.040047261	0.008329372
189	0.011509	0.001831	-0.04746813	0.004237471	-0.045907783	-0.011543725
190	0.0178005	0.00179	0.098999934	0.002492937	0.010199965	0.004092067
191	0.019831	0.001984	-0.034279395	0.004549741	0.054360855	0.008792047
192	0.028278	0.002207	-0.009492469	0.001926996	-0.128438008	0.004530587
193	0.0251435	0.0021985	-0.010326035	0.005952499	0.026046997	0.00034463
194	0.006652	0.00223	-0.039053383	0.000686831	0.068281068	0.003116367
195	0.0239745	0.002281	0.002076443	0.00645482	0.169565846	0.007347406
196	0.0620035	0.002072	0.061820795	-0.000428257	0.144532432	0.000318675
197	0.072487	0.001971	0.028237133	0.000191461	-0.056435218	0.008156792
198	0.0279695	0.002119	-0.010088154	0.002833257	-0.05971557	0.004428315
199	0.035057	0.00224	-0.07908602	-0.002000806	0.024561762	0.003711543
200	0.031089	0.002342	0.08468353	-0.003386154	0.092711464	-0.003167468
201	0.034243	0.002466	0.057139744	0.004336548	-0.114534092	0.005880699
202	0.032572	0.002872	0.083427767	0.005088258	0.039139398	-0.003286139
203						
204		RMSE	0.05132238	0.00310784	0.076285474	0.006119538
205		MAE	0.040254477	0.002500529	0.061599655	0.004806835



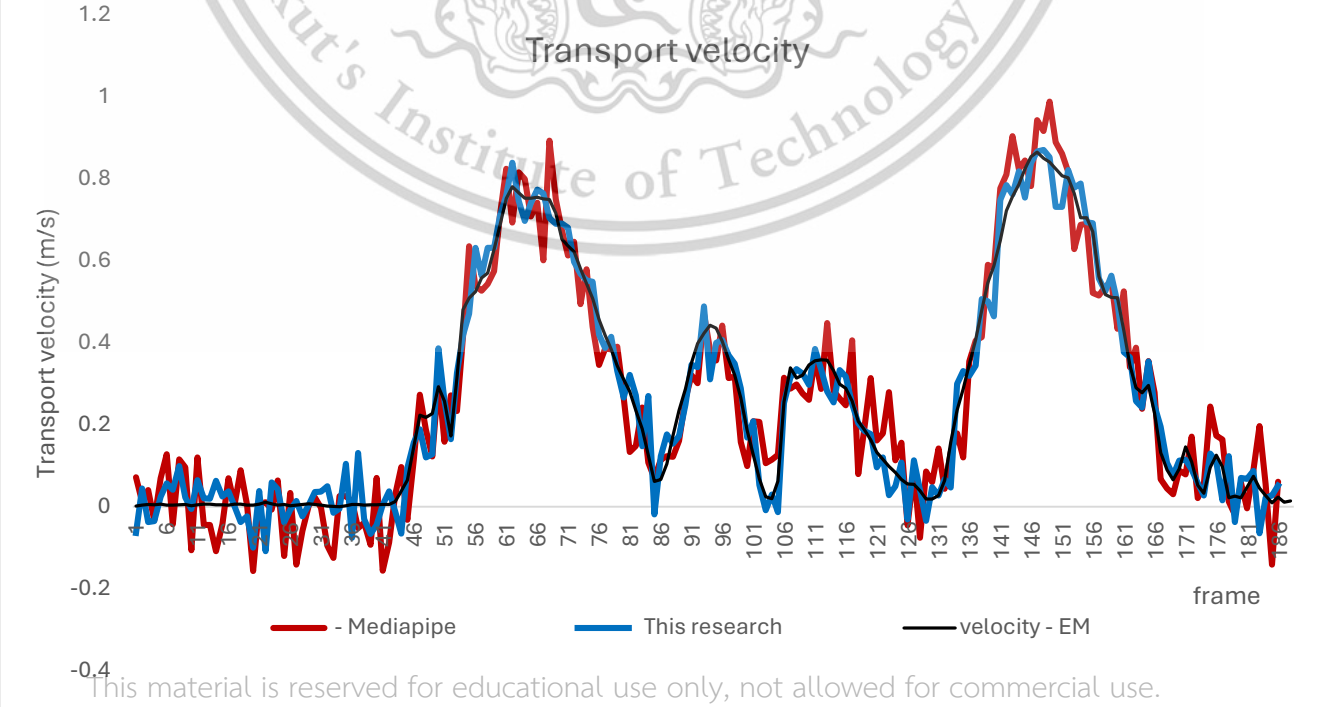


Table 5 Result from trial5

frame	velocity - EM	aperture - EM	This research	aperture - This research	- Mediapipe	aperture - Mediapipe
1	0.001649	0.0043175	0.039838827	0.004458098	-0.064306633	0.005416207
2	0.002027	0.004365	0.038292238	0.005234395	0.005786515	0.011636615
3	0.0020905	0.004343	-0.032963519	0.004234879	-0.035455146	-0.003834034
4	0.005832	0.0042565	0.020829356	-0.001164479	0.06433354	0.00329344
5	0.004098	0.004263	-0.075776044	0.007583058	-0.079320558	0.001715223
6	0.0055985	0.004398	0.03641816	0.008192801	-0.088187032	0.006499208
7	0.005235	0.00446	0.064659036	0.001953073	-0.041790154	0.010867103
8	0.00757	0.00436	0.01329636	0.005399424	0.019792584	0.011562153
9	0.006107	0.0042605	0.08894155	0.001560739	0.035609428	-0.005852997
10	0.007374	0.004091	0.064063448	0.008486065	0.085690207	0.00678121
11	0.009947	0.003981	-0.013951903	0.003141295	0.02493989	0.010311663
12	0.010577	0.0039935	-0.125368445	0.00625587	-0.05465291	0.014498912
13	0.005293	0.004128	-0.026359039	0.006442791	0.07265195	-0.001726116
14	0.003247	0.004209	0.036991674	0.011735663	-0.062471113	0.007268162
15	0.0034505	0.0042345	0.010951322	0.004886655	0.056467417	0.007775693
16	0.004502	0.0042085	-0.022009052	0.002619653	0.105988114	0.010139918
17	0.004175	0.004181	0.040386884	0.002620958	0.102858638	0.011197798
18	0.001423	0.004188	0.003277765	0.004222847	0.038401126	-0.001782338
19	0.003019	0.0042015	0.009213403	0.003249642	0.060353601	-0.000778438
20	0.004128	0.004206	0.047850773	0.003380297	0.100500297	0.007034467
21	0.002112	0.004272	-0.000898883	0.004020583	0.00960585	-0.006403748
22	0.00327	0.004368	0.069570578	0.002753833	0.01893758	0.004112409
23	0.002542	0.004329	-0.011565108	0.004565951	0.03261948	0.009976155
24	0.004204	0.004411	0.026837349	0.004449922	0.020649277	0.007624532
25	0.0073325	0.004275	-0.066974867	0.010454971	-0.079665752	0.00021226
26	0.010826	0.004046	0.047691847	0.001472302	0.050720333	0.016987932
27	0.035531	0.004282	0.135784716	0.007066519	-0.017526069	-0.001151725
28	0.110565	0.004157	0.130290081	0.004424878	0.048802609	-0.002021983
29	0.121566	0.003566	0.045837123	0.00100664	0.097837371	0.004951169
30	0.128447	0.004222	0.145125943	-0.000680583	0.047208126	-0.010769814
31	0.133419	0.004525	0.082192602	0.007252623	0.128396533	0.004187303
32	0.157448	0.003172	0.177350511	0.004088902	0.180897483	0.002115106
33	0.178859	0.0026395	0.120610917	0.009492128	0.142117343	0.003236272
34	0.210599	0.006077	0.151483034	0.001258625	0.120729126	0.013328204
35	0.274803	0.004995	0.285209735	0.006652384	0.177661746	0.010194264
36	0.3766135	0.00619	0.355685063	0.003491158	0.452828924	0.005828321
37	0.5390635	0.010833	0.543659566	0.009652246	0.373556764	0.011866043
38	0.60468	0.015109	0.614731202	0.009216116	0.63241653	0.009693001
39	0.600771	0.0196995	0.67195457	0.02343909	0.577143861	0.017881771
40	0.658486	0.0259745	0.685666959	0.025613834	0.630729997	0.03103614
41	0.719726	0.030971	0.701628322	0.03010943	0.776497707	0.026432732
42	0.757339	0.0362045	0.769040333	0.035607265	0.847946662	0.032102607
43	0.829478	0.043766	0.836254132	0.046812141	0.897154202	0.047417667
44	0.891523	0.049824	0.920470795	0.048697118	0.877722673	0.052758081
45	0.9120015	0.05598	0.898835556	0.056641958	0.751007325	0.054431469
46	0.889827	0.0647115	0.893868056	0.061944892	0.773714406	0.058652882
47	0.877086	0.070692	0.920978811	0.0675593	0.875867139	0.08472371
48	0.867095	0.0752605	0.855840003	0.076488778	0.914799956	0.074467726
49	0.827684	0.07996	0.788453148	0.080655377	0.982092781	0.077749302
50	0.807492	0.082969	0.780968801	0.079828883	0.797040327	0.084587609
51	0.782088	0.085672	0.873477462	0.087374023	0.748591465	0.072422564
52	0.710408	0.0892885	0.634348416	0.086978507	0.793164812	0.083283242
53	0.669177	0.091815	0.740894635	0.088211188	0.588373366	0.09619649
54	0.6400115	0.093582	0.676944028	0.09213644	0.610196638	0.100533063
55	0.60167	0.0951825	0.575241724	0.100628861	0.551891785	0.082590184
56	0.55735	0.096248	0.606569738	0.095512412	0.54010846	0.097166244
57	0.50632	0.097075	0.554017761	0.095797771	0.592452389	0.100842411
58	0.448156	0.096913	0.42980998	0.097262943	0.396494227	0.108975445
59	0.391471	0.09564	0.418486405	0.097342323	0.404400256	0.105682469
60	0.3336095	0.093051	0.358434922	0.089580569	0.263441246	0.101050464
61	0.2654135	0.087397	0.255500786	0.085698721	0.312121329	0.092345971
62	0.205855	0.081478	0.206232568	0.077229072	0.164655042	0.079207372
63	0.156276	0.075331	0.169784651	0.070859034	0.296576427	0.075106907
64	0.129162	0.069649	0.18604975	0.068435336	0.111156996	0.071970538
65	0.139944	0.068053	0.146829877	0.065308856	0.165813185	0.061155242
66	0.1799405	0.06786	0.141803447	0.070113617	0.217699723	0.065517816
67	0.2105985	0.067197	0.266945365	0.063860421	0.119810552	0.066748222
68	0.233797	0.066482	0.230497074	0.066379414	0.299979419	0.069811064
69	0.282143	0.065781	0.256035209	0.067573395	0.406323796	0.066163001
70	0.350505	0.0652095	0.37706918	0.068666926	0.343916138	0.073087358
71	0.39009	0.065092	0.385890328	0.064147988	0.365430049	0.061334419
72	0.3983115	0.065114	0.381761142	0.070047551	0.242318628	0.069670816
73	0.40214	0.065117	0.404248808	0.065005975	0.458264297	0.067807589
74	0.396259	0.065125	0.364140482	0.068582012	0.375199412	0.075450845
75	0.3620215	0.0652585	0.366860164	0.063128047	0.388825005	0.074765815
76	0.2932115	0.065432	0.289523201	0.062972466	0.363006341	0.071836466
77	0.232349	0.065553	0.178781354	0.06156731	0.033573295	0.065794315
78	0.1834755	0.0656875	0.166858573	0.065108636	0.081937206	0.058048087
79	0.1006085	0.0658195	0.13957301	0.062511332	0.207893959	0.058620895
80	0.034358	0.065897	-0.014442595	0.061717221	0.080420693	0.07032938
81	0.024219	0.06586	-0.073840838	0.065471764	0.080125906	0.064707653
82	0.045925	0.065789	0.020632686	0.066692689	0.144843745	0.064669636
83	0.172477	0.065939	0.161437498	0.062721173	0.15208598	0.061410592
84	0.3302735	0.0661515	0.329800182	0.066518785	0.421945711	0.054102526
85	0.336396	0.0661915	0.288798867	0.067371218	0.221876068	0.060805476
86	0.316903	0.066299	0.187699041	0.068022536	0.228027641	0.060576406
87	0.336153	0.066452	0.315674114	0.066633946	0.353566391	0.054489496
88	0.3474555	0.066479	0.334928877	0.073831691	0.340095939	0.067581354
89	0.347537	0.06639	0.320102653	0.066604669	0.350190083	0.077748665
90	0.3299765	0.0663095	0.2498632	0.065193799	0.469284754	0.063833711
91	0.305569	0.0661685	0.379012522	0.063881986	0.316711825	0.069372641
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93	0.2415625	0.0659945	0.204959586	0.063228263	0.220723926	0.074049644
94	0.2095415	0.065936	0.234760917	0.065947979	0.297496642	0.060182543
95	0.187199	0.065887	0.267539461	0.069202903	0.205645022	0.073103731
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97	0.1495175	0.0662265	0.199890276	0.071883307	0.124366944	0.058361422
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106	0.160658	0.075643	0.184685607	0.075531914	0.08940239	0.076730378
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109	0.332192	0.0822275	0.395090112	0.079099741	0.472883913	0.09165553
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112	0.535848	0.0805595	0.561843636	0.084777836	0.364911256	0.083999246
113	0.596453	0.078219	0.622485568	0.082101498	0.589271291	0.083904137
114	0.6599055	0.0749985	0.64241196	0.072671599	0.55436707	0.074233667
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121	0.8099395	0.031127	0.850715638	0.032706942	0.725293423	0.034016926
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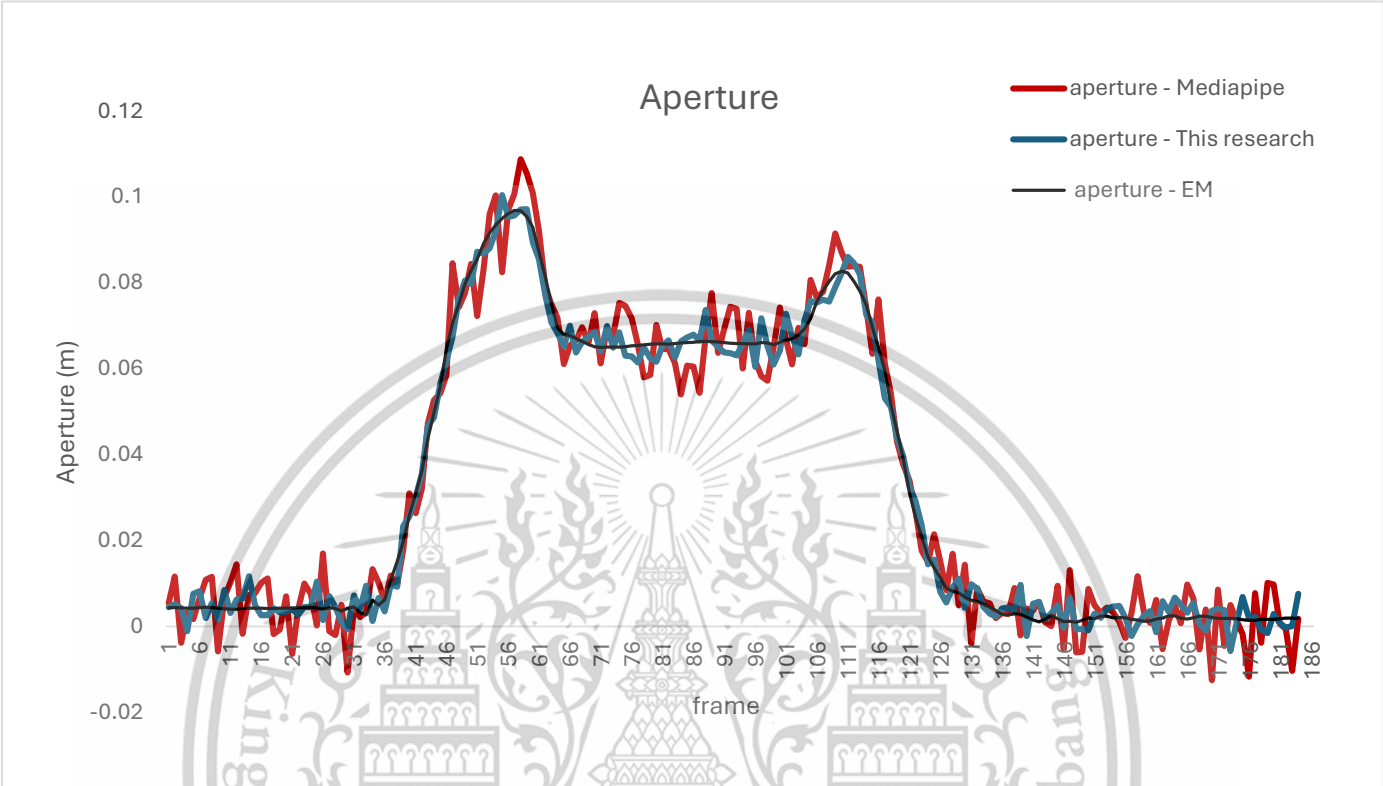

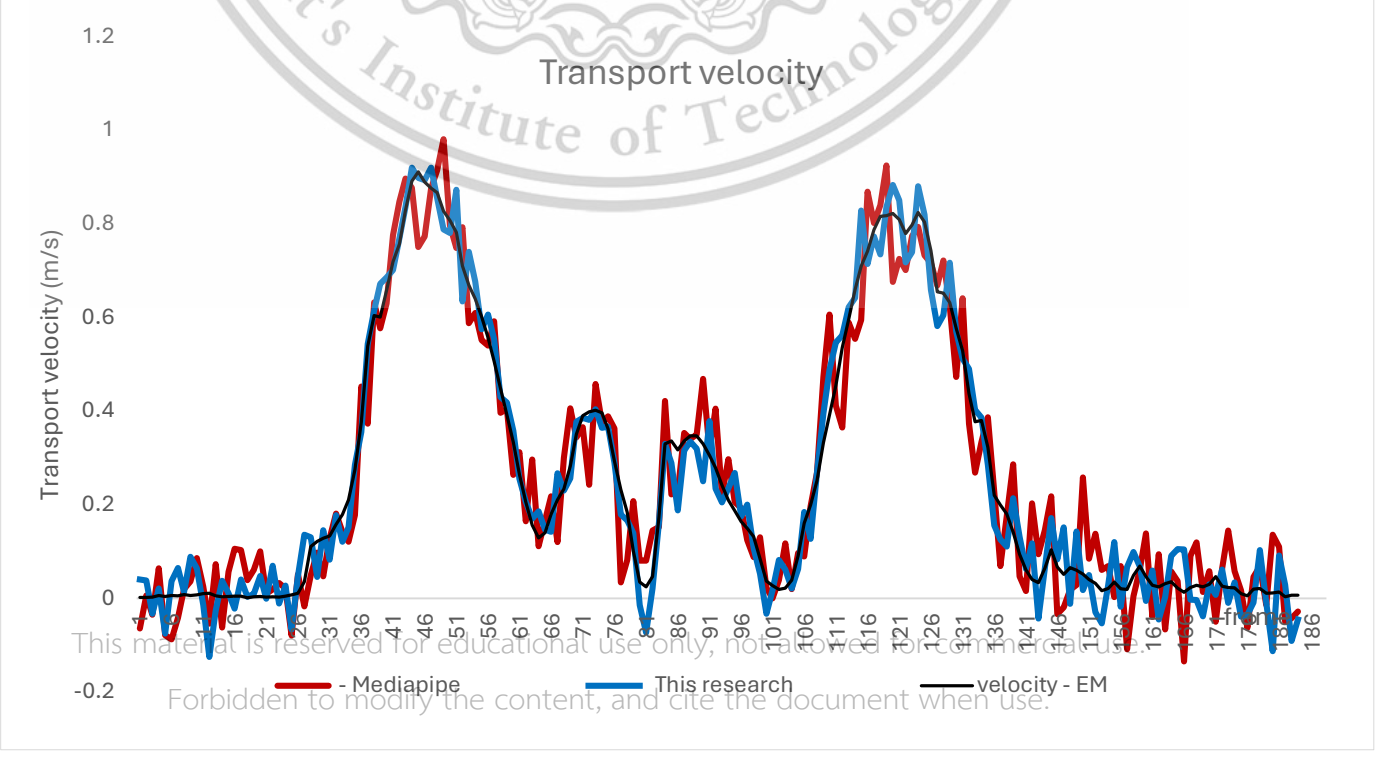

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