CSE 162 Mobile Computing

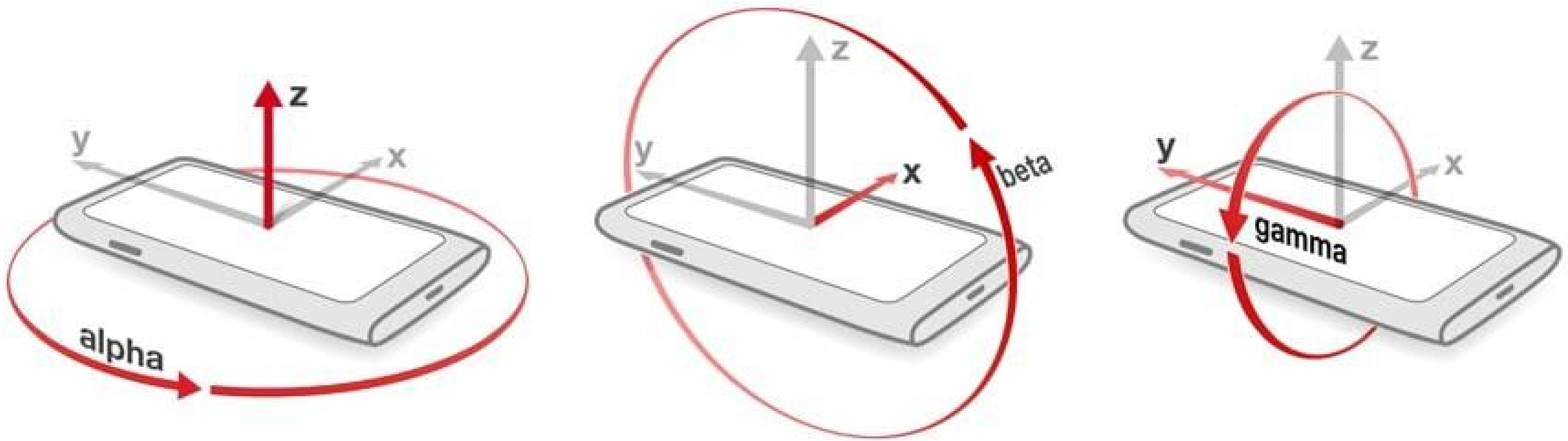
Orientation and Step Counting

Hua Huang

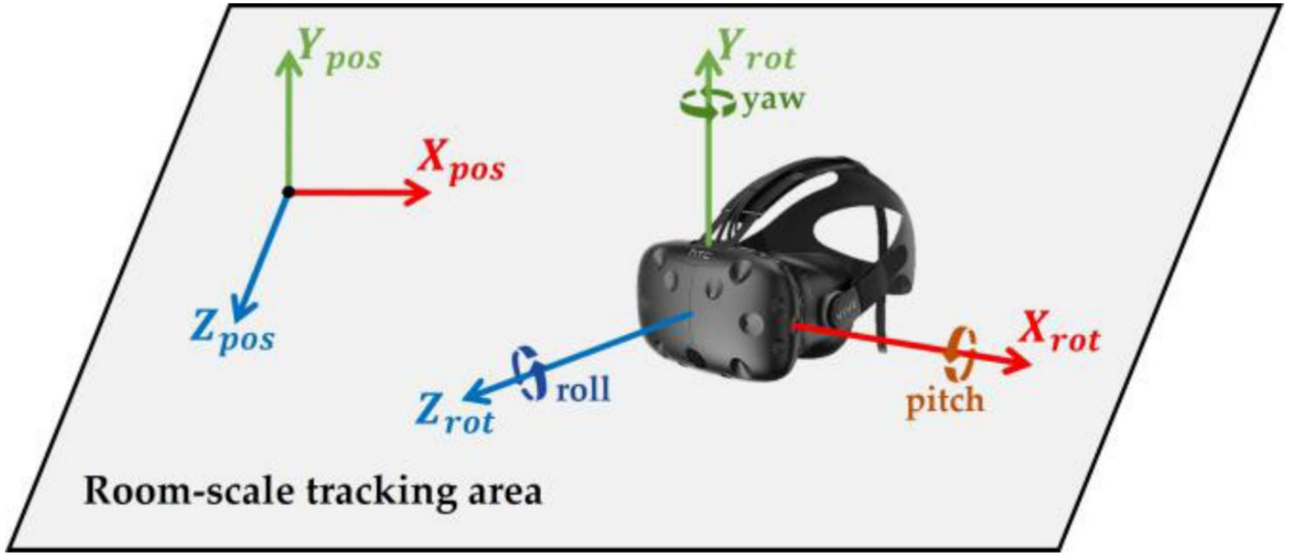
Virtual Sensor: 3D Orientation

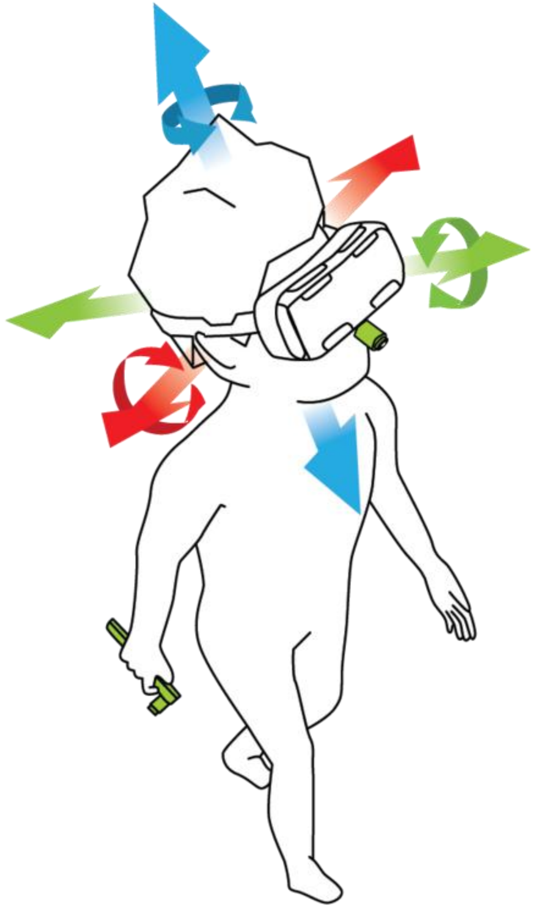
Question:

How do we know the orientation of the phone?

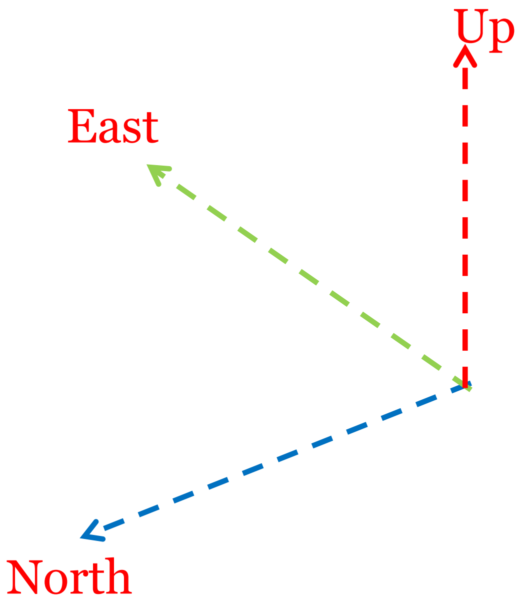


• Orientations of the VR goggle?

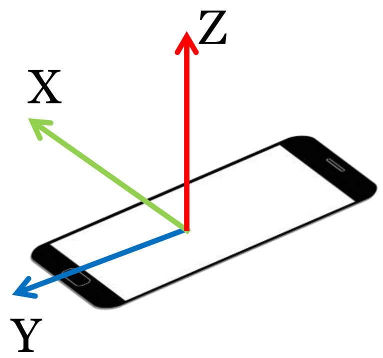




Coordinate frames

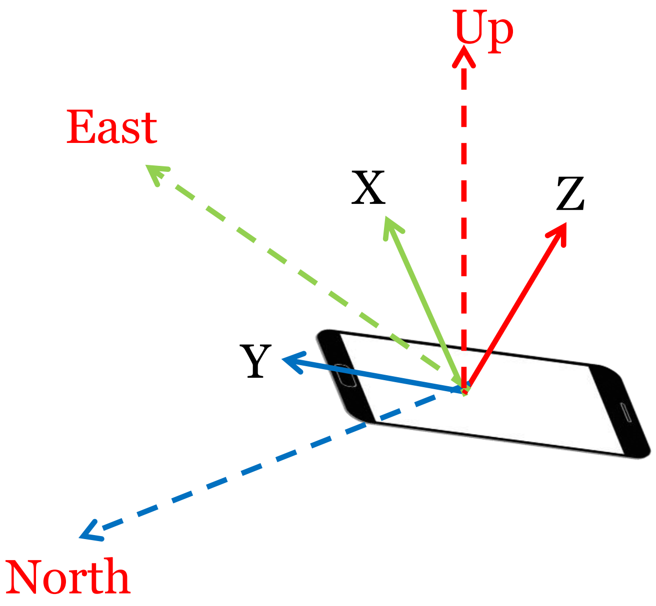


Global Frame



Local Frame

Consider a phone in a random orientation

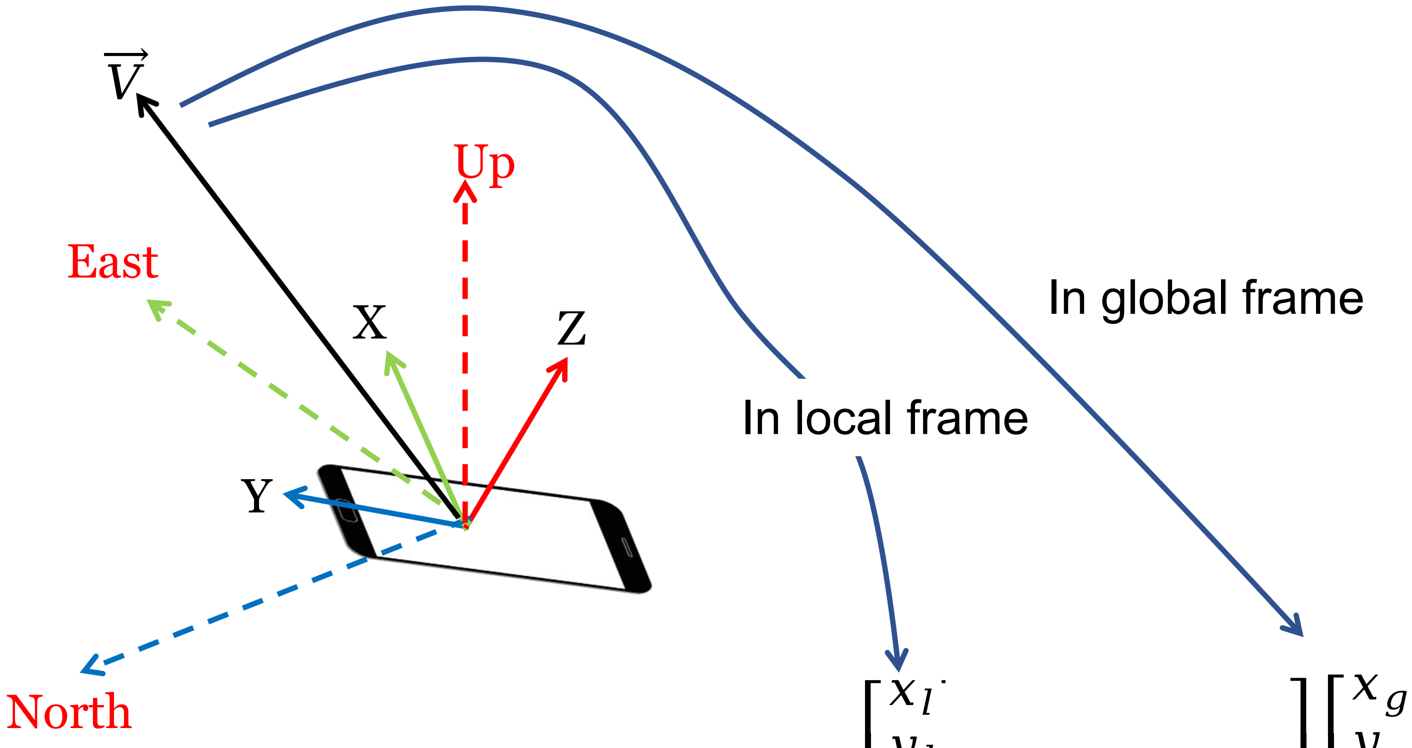


3D Orientation captures the misalignment between global and local frames

Gravity Sensor

- A virtual sensor
- Calculated using accelerometer
- Always points to the earth

Rotation Matrix



$$\begin{bmatrix} x_l \\ y_l \\ z_l \end{bmatrix} \qquad \begin{bmatrix} \quad \end{bmatrix} \begin{bmatrix} x_g \\ y_g \\ z_g \end{bmatrix}$$

R is the 3x3 Rotation Matrix

3x3 Rotation matrix captures the full 3D orientation

How can we estimate rotation matrix?

Key idea   use globally known reference vectors

which can also be measured in the local frame of reference

- Gravity
- Magnetic North

Gravity equation

Gravity globally known, measurable in local frame with gravity sensor

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} \qquad \begin{bmatrix} \ \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix} \qquad\qquad \begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} \qquad \begin{bmatrix} \ \end{bmatrix} \begin{bmatrix} 0 \\ M \\ 0 \end{bmatrix}$$

Magnetic north, globally known, measurable in local frame with magnetometer

6 equations and 9 unknowns (3x3 rotation matrix) can we solve ?

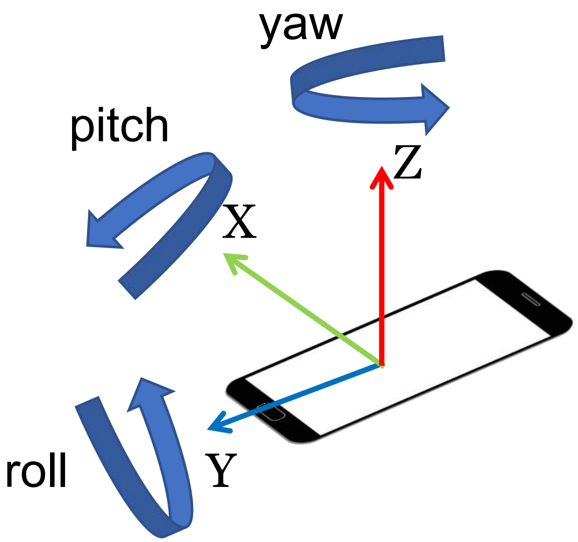
Yes, these 9 unknowns are all not independent (rotation matrix satisfies special properties)

- It does not change length of a vector
- Columns are orthogonal unit vectors

The above 6 equations are sufficient to solve the rotation matrix

Gravity Sensor and Magnetometer can be used to determine the rotation matrix (3D orientation)

Decomposing the rotation matrix



$$\begin{bmatrix} \text{3x3 Rotation Matrix R} \end{bmatrix} = \begin{bmatrix} \cos(pitch) & 0 & -\sin(pitch) \\ 0 & 1 & 0 \\ \sin(pitch) & 0 & \cos(pitch) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(roll) & \sin(roll) \\ 0 & -\sin(roll) & cos(roll) \end{bmatrix} \begin{bmatrix} \cos(yaw) & -\sin(yaw) & 0 \\ \sin(yaw) & \cos(yaw) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Orientation can be represented as 3D yaw, pitch, roll

Estimating yaw, pitch, roll will determine the orientation

Gravity equation

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} \text{Rotation Matrix R} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix}$$

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} \cos(pitch) & 0 & -\sin(pitch) \\ 0 & 1 & 0 \\ \sin(pitch) & 0 & \cos(pitch) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(roll) & \sin(roll) \\ 0 & -\sin(roll) & cos(roll) \end{bmatrix} \boxed{\begin{bmatrix} \cos(yaw) & -\sin(yaw) & 0 \\ \sin(yaw) & \cos(yaw) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix}}$$

Gravity equation

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} \text{Rotation Matrix R} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix}$$

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} \cos(pitch) & 0 & -\sin(pitch) \\ 0 & 1 & 0 \\ \sin(pitch) & 0 & \cos(pitch) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(roll) & \sin(roll) \\ 0 & -\sin(roll) & cos(roll) \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix}$$

Gravity output does not depend on yaw!

Hence, yaw cannot be estimated using gravity

Accelerometer equation

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} \text{Rotation Matrix R} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix}$$

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} -\sin(pitch).\cos(roll).g \\ -\sin(roll).g \\ -\cos(pitch).\cos(roll).g \end{bmatrix}$$

The above equations estimate pitch and roll

Magnetometer equation

$$\begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} = \boxed{\text{Rotation Matrix R}} \begin{bmatrix} 0 \\ M \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} = \begin{bmatrix} \cos(pitch) & 0 & -\sin(pitch) \\ 0 & 1 & 0 \\ \sin(pitch) & 0 & \cos(pitch) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(roll) & \sin(roll) \\ 0 & -\sin(roll) & cos(roll) \end{bmatrix} \begin{bmatrix} \cos(yaw) & -\sin(yaw) & 0 \\ \sin(yaw) & \cos(yaw) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ M \\ 0 \end{bmatrix}$$

Magnetometer equation

$$\begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} = \begin{bmatrix} \text{Rotation Matrix R} \end{bmatrix} \begin{bmatrix} 0 \\ M \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} = \begin{bmatrix} \cos(pitch) & 0 & -\sin(pitch) \\ 0 & 1 & 0 \\ \sin(pitch) & 0 & \cos(pitch) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(roll) & \sin(roll) \\ 0 & -\sin(roll) & cos(roll) \end{bmatrix} \begin{bmatrix} \cos(yaw) & -\sin(yaw) & 0 \\ \sin(yaw) & \cos(yaw) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ M \\ 0 \end{bmatrix}$$

Pitch, roll known from accelerometer

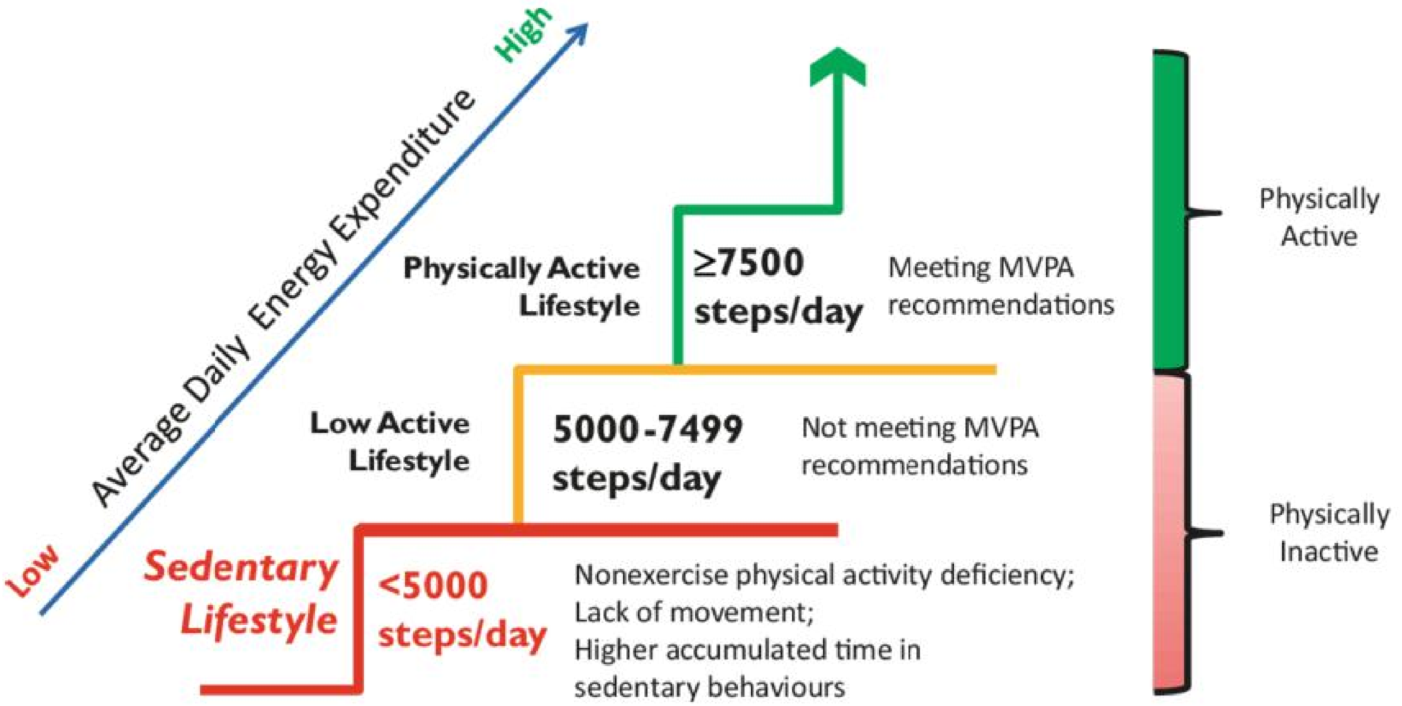
Unknown yaw can be determined from above equations

yaw, pitch, roll together determine the rotation matrix (3D orientation) of a system

Virtual Sensor: Step Counting

Sedentary Lifestyle

- Sedentary lifestyle
  - Increases risk of diabetes, heart disease, dying earlier, etc
  - Kills more than smoking!!
- Categorization of sedentary lifestyle based on step count:
  - "A step-defined sedentary lifestyle index: < 5000 steps/day" (2013)



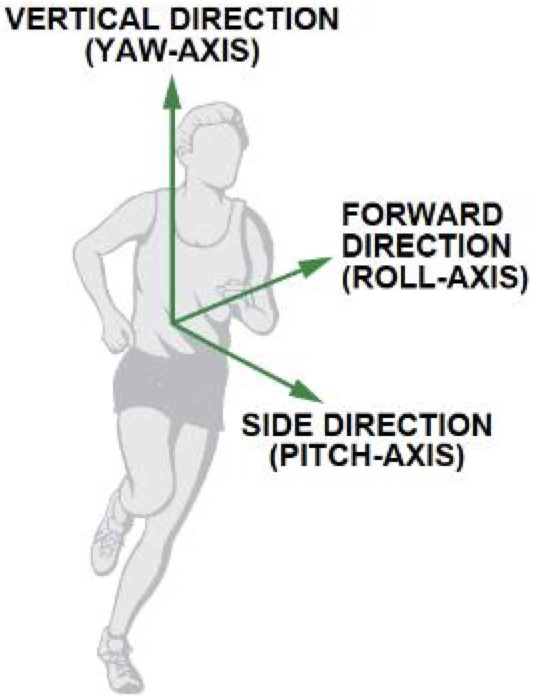
Step Count Mania

- Everyone is crazy about step count these days
- Pedometer apps, pedometers, fitness trackers, etc
- Tracking makes user aware of activity levels, motivates them to exercise more

Benefits mobile step counters

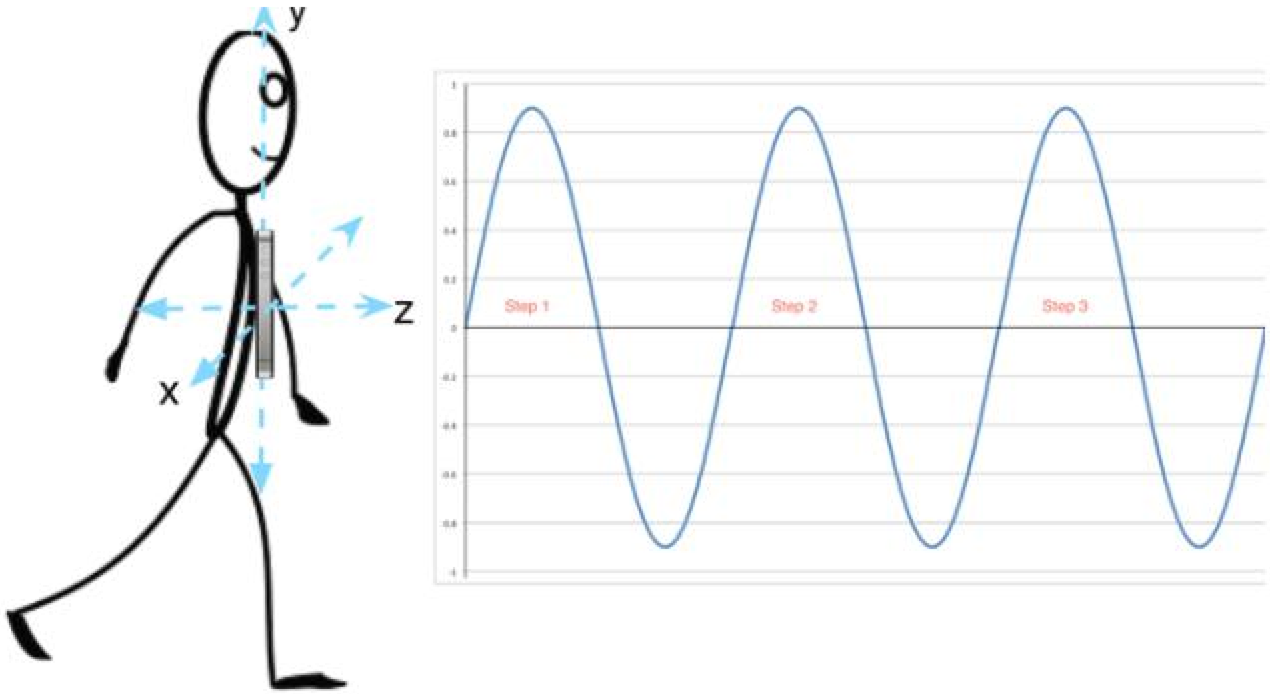
- Always on. Everywhere. Continuous monitoring.
- Low-cost
- Better privacy than computer vision

Definition of each axis



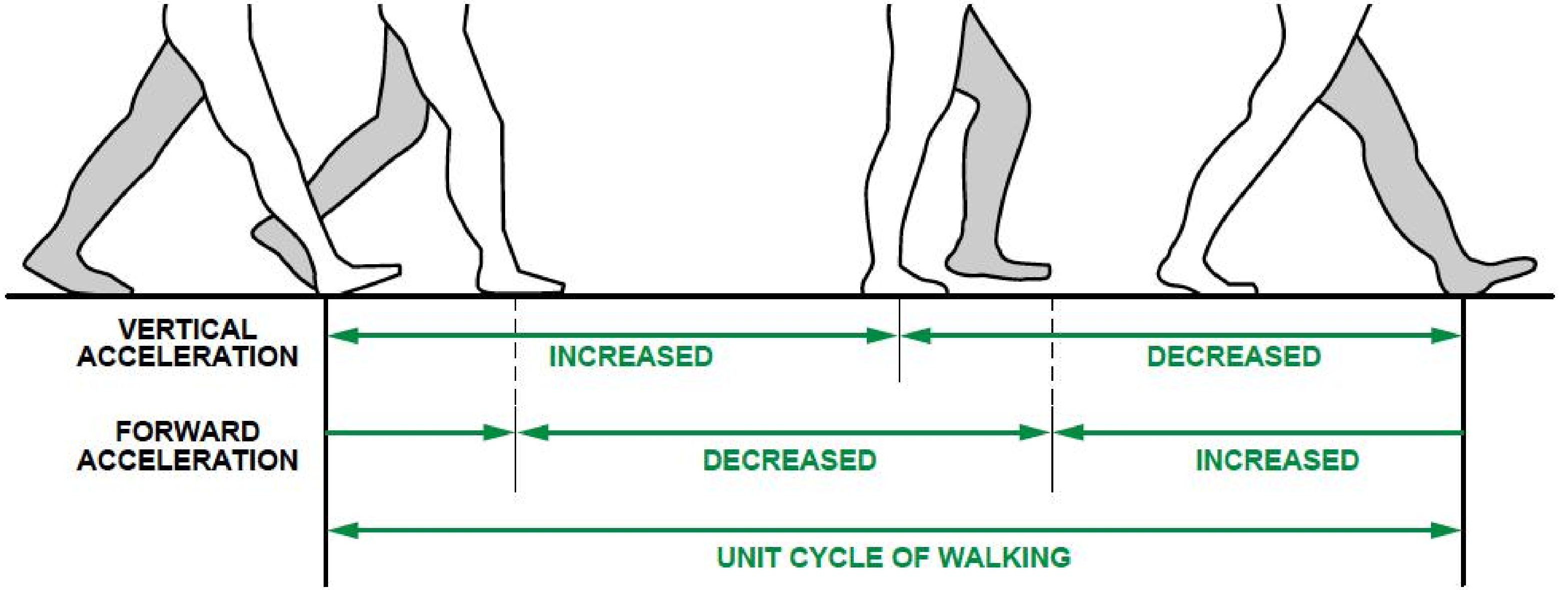
Ideal sensor data

- In an ideal situation, you would like to see a signal like this.
  - One of the axes of the phone is along the direction of gravity, and the steps can be clearly observed in the signal.
- But in practice, the data often deviates from the ideal case



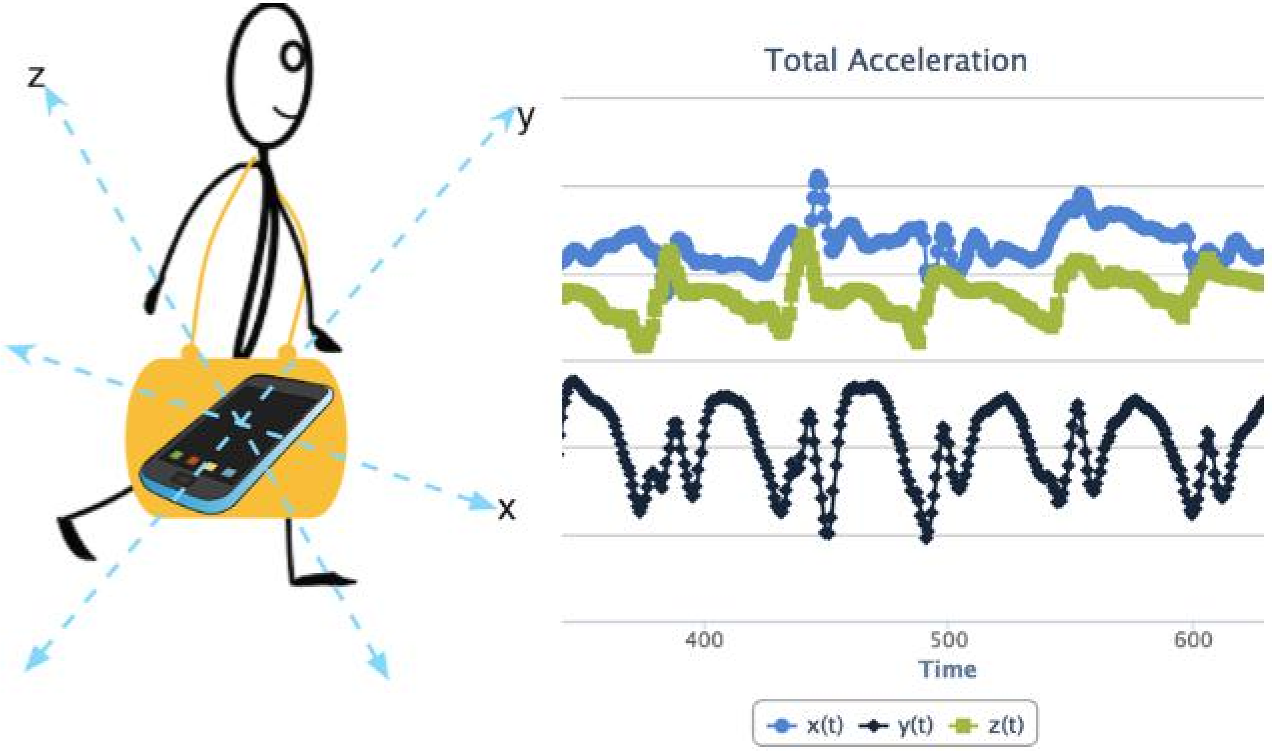
The Nature of Walking

- Vertical and forward acceleration increases/decreases during different phases of walking
- Walking causes a large periodic spike in one of the accelerometer axes
- Which axes (x, y or z) and magnitude depends on phone orientation



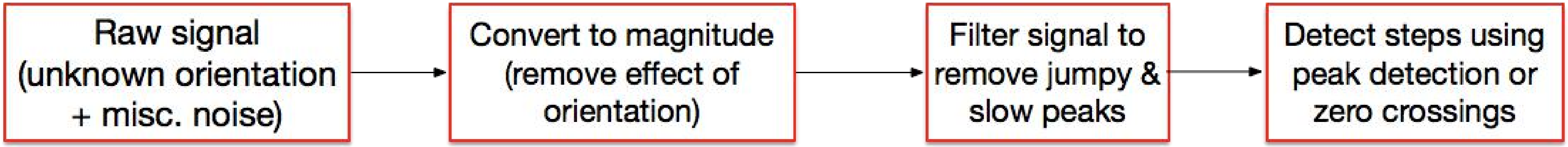
Accelerometer signal in a real-world situation

- A more realistic signal is shown
  - some component of the user acceleration and gravity is present along all three axes.
  - The measurements are influenced by the phone orientation
- we need to design an *orientation-independent* algorithm to detect steps.



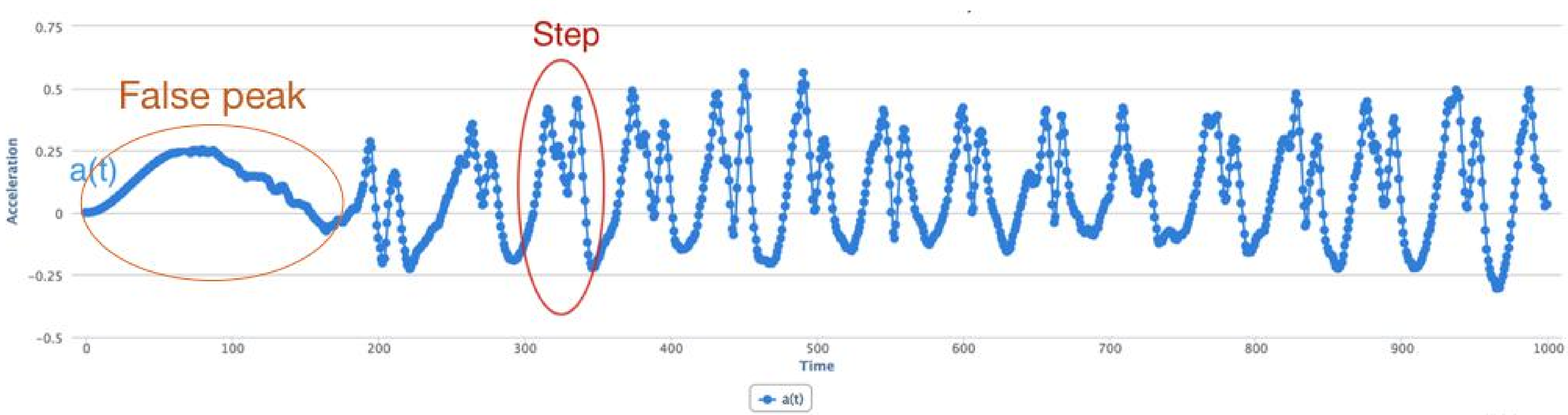
Step Detection Algorithm

- The key insight in our method is to convert the 3-axis signal into a one axis magnitude signal, and then extract steps from this signal.



Step 1: Extract Signal Magnitude

- take the magnitude of the entire acceleration vector i.e. $\sqrt{x^2 + y^2 + z^2}$, where x, y, and z are the readings of the accelerometer along the three axes.
- The signal is not dependent on phone orientation now



Step 2: Filter the signal to remove noise

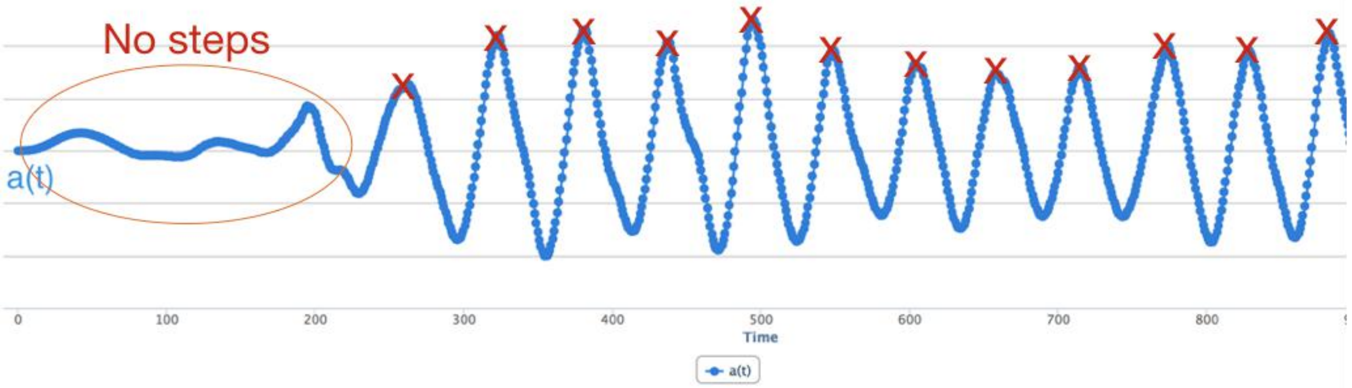
- What noises exist in the data?
  - **Jumpy peaks**: Since the phone is often carried in a pocket/purse, it can jiggle a little with each step. Also, some users have a bounce in their step, so even though they are taking a single step, the phone can bounce multiple times within this step.
  - **Short peaks**: Small peaks can occur when a user is using a phone (e.g. making a call or using an app).
  - **Slow peaks**: Slow peaks can occur when the phone is moved or due to movements of the leg while sitting (if the phone is in the pant pocket)

Filtering

- To remove these sources of noise, we are going to use frequency-domain noise removal.
- Notice that we need to remove high frequency variations like jumpy peaks and low frequency variations like slow peaks.
- A simple solution is to use a filter that keeps only frequencies relating to walking and removes the rest.

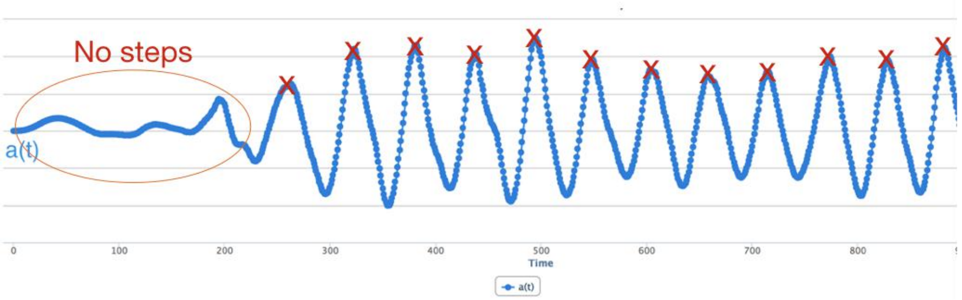
Filtering

- Typical walking pace may be under three steps a second (3 Hz) and over half step a second (0.5Hz), so we remove all frequencies above 5 Hz and below 0.5 Hz (just to give some margin for error)
- Even after we remove low and high frequency peaks, we may be left with some short peaks.
  - A simple way to deal with this is to look only for large peaks and ignore small peaks.

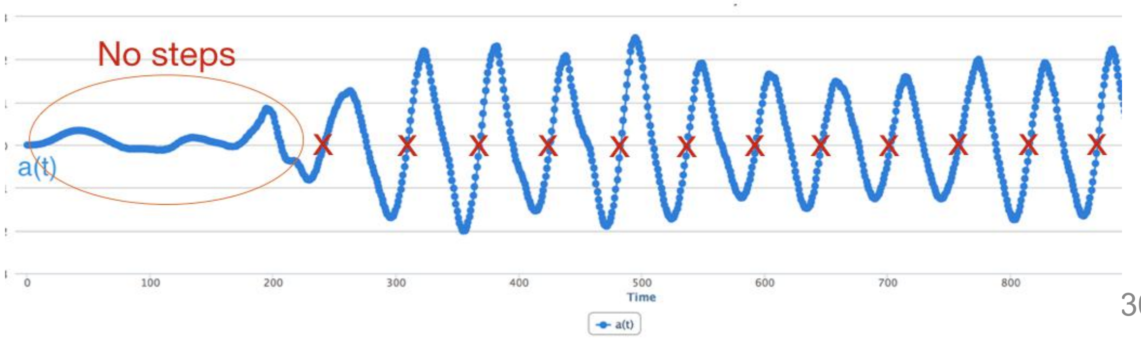


Step 3: Detect Steps

- Approach 1: Find signal peaks

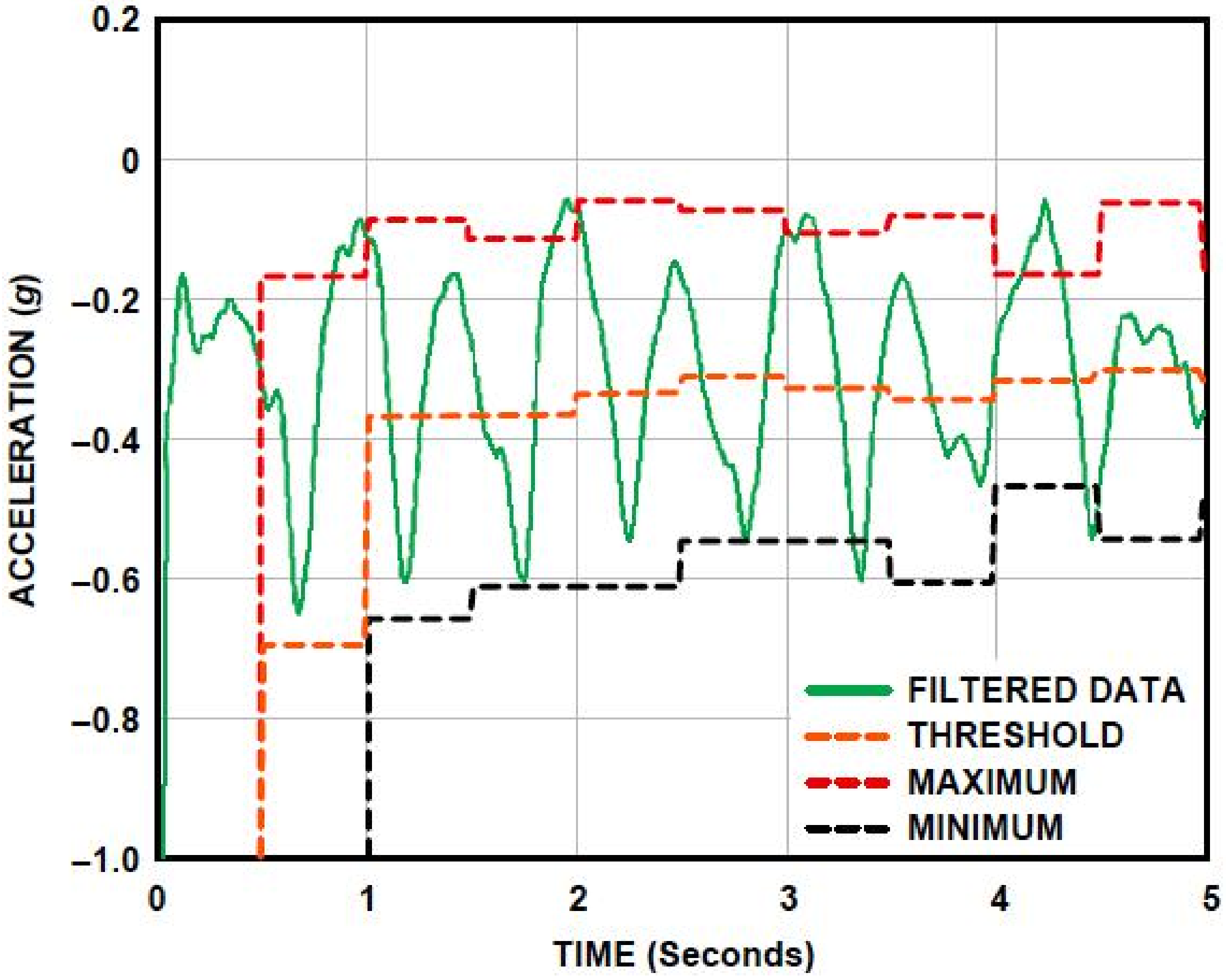


- Approach 2: Zero crossing:
  - Subtract the mean for each window and look at zero crossings i.e. times when the signal crosses from the negative to positive in the upward direction



Dynamic Threshold-based Step Detection

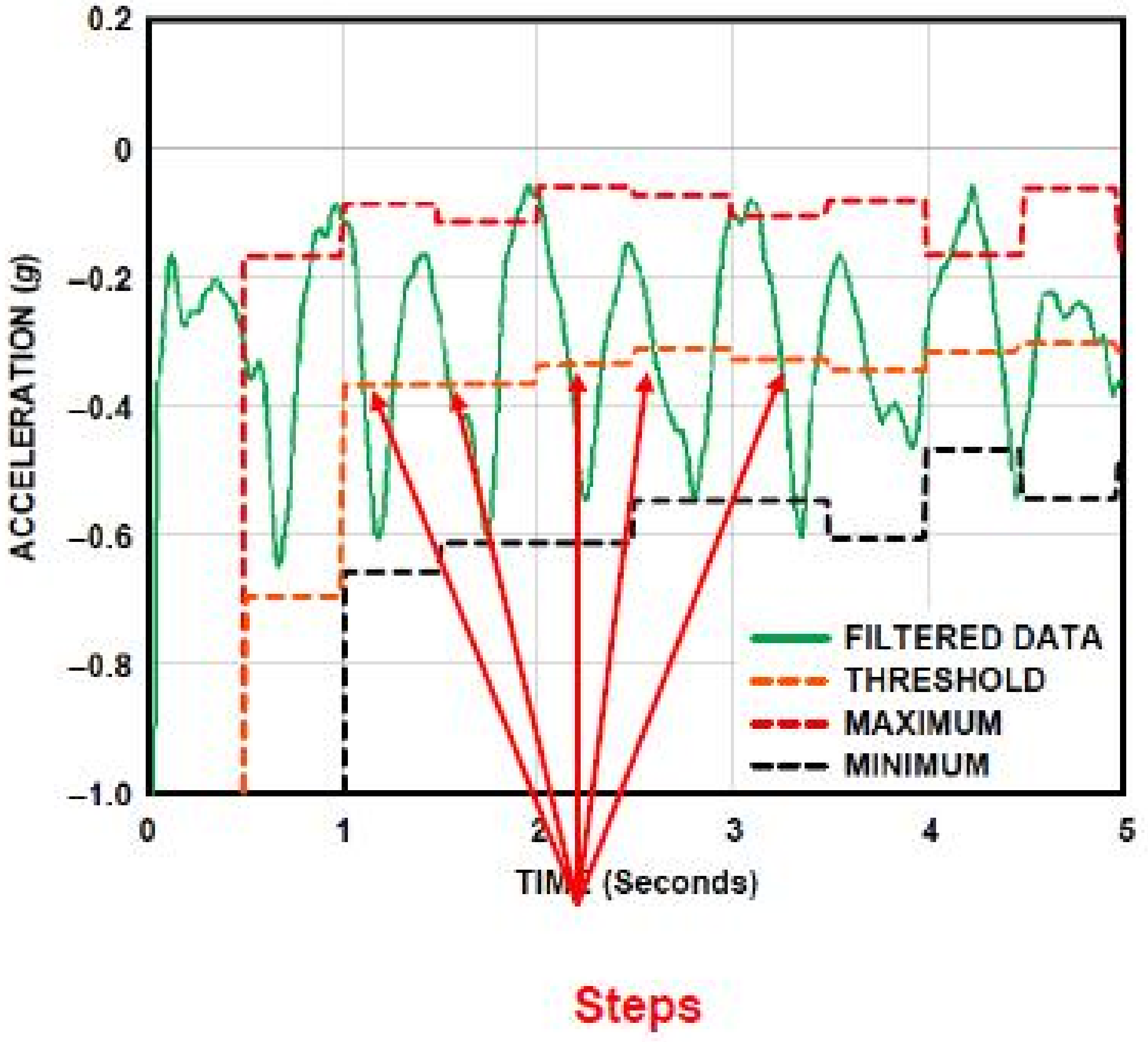
- Focus on accelerometer axis with largest peak
- Would like a threshold such that each crossing is a step
- Track min, max values observed every 50 samples
- Compute ***dynamic threshold: (Max + Min)/2***



Step Detection Algorithm

A step is

- Indicated by crossings of dynamic threshold
- Defined as negative slope (sample_new < sample_old) when smoothed waveform crosses dynamic threshold



Distance Estimation

- Calculate distance covered based on number of steps taken
  - *Distance = number of steps ×distance per step*
- Distance per step (stride) depends on user's height (taller people, longer strides), and step frequency
- Using person's height, can estimate their stride, then number of steps taken per 2 seconds

Steps per 2 s	Stride (m/s)
0~2	Height/5
2~3	Height/4
3~4	Height/3
4~5	Height/2
5~6	Height/1.2
6~8	Height
>=8	1.2 × Height

Calorie Estimation

- To estimate speed, remember that speed = distance/time. Thus,
  - *Speed (in m/s) = (no. steps per 2 s ×stride (in meters))/2s*
- Calorie expenditure, which depends on many factors
  - Body weight, workout intensity, fitness level, etc
- Empirical simplified equation:
  - *Calories (C/kg/h) = 1.25 ×speed (m/s) ×3600/1000 = 4.5 ×speed (m/s)*

Limitations and Future Work

- Strong assumptions on how the users walk.
    - What about short-interval, high intensity exercise?
    - What about the other calorie expenditures? Standing vs sitting
- Currently, dedicated system for each activities. General activity recognition is still under research.