FUNDAMENTALS OF A SELF-BALANCING ROBOT

Manual - 1

What is a Self-Balancing Robot?

A self-balancing robot is basically an **inverted pendulum** that tries not to fall.

- A pendulum naturally hangs down (stable).
- If you flip the pendulum upside-down (robot standing on wheels) → it becomes unstable.
- The robot **continuously measures its tilt** and uses motors to keep itself upright.

This system is **inherently unstable**, meaning it **must constantly correct itself** to stay balanced.
That is the core challenge.

The Inverted Pendulum Model (The Real Science)

A two-wheel balancing robot behaves like this:

- Center of gravity above the wheel axle
- Gravity tries to make it fall forward/backward
- Motors try to rotate the wheels to bring it back upright

This dynamic is identical to balancing a **broomstick on your finger**.
Your brain constantly:

1. Checks tilt
2. Predicts where it is going
3. Moves your hand
4. Corrects the tilt

Your robot will do the same using:

- MPU6050 → "brain sensors"
- Complementary filter → "your inner ear"
- PID controller → "your brain output"
- Motors → "your muscles"

Why You Need a Tilt Angle

The robot must know:

- **How much it is tilted (angle)**
- **How fast it is falling (angular velocity)**

These two values are enough to balance anything.

But where do they come from?

→ **Accelerometer** gives tilt angle (but noisy)
→ **Gyroscope** gives rotation rate (but drifts)

This leads to the next part.

Accelerometer vs Gyroscope (The Heart of Everything)

🔶 Accelerometer:

Measures *acceleration*, but when stationary it gives **gravity direction**
→ You can calculate tilt angle from gravity.

Good:

- Accurate for slow movement
- Absolute reference
  Bad:
- Very noisy
- Reacts to vibrations
- If robot accelerates, reading becomes confusing

This is why you CANNOT use only the accelerometer.

🔶 Gyroscope:

Measures *rotational speed* (°/s).
If you integrate gyro angle:

$$\theta = \int \omega dt$$

You get tilt angle.

Good:

- Very smooth
- No noise
- Excellent for fast movements

Bad:

- It drifts with time
- Small bias → huge drift

So you CANNOT use only the gyro.

Complementary Filter (The Secret That Makes Robots Work)

Complementary = **"two things that complete each other"**

- Gyro is good at high frequencies (fast motion)
- Accelerometer is good at low frequencies (long term reference)

So we combine them:

- Low-pass filter for accelerometer
- High-pass filter for gyroscope

$$\text{Angle} = 0.98(\text{Angle} + \text{Gyro} \cdot dt) + 0.02(\text{Accel Angle})$$

This gives the perfect tilt angle for balancing.

Why a Robot Falls (Science)

A balancing robot falls because:

- Center of gravity is high
- Gravity creates a torque trying to rotate it
- Small tilt quickly becomes large tilt
- System is unstable without feedback

This is why PID control is needed.

PID Control (The Brain of The Robot)

PID = Proportional + Integral + Derivative.

- **P (Proportional)**
  Reacts to how tilted the robot is right now.
- **I (Integral)**
  Fixes long-term bias (like floor tilt or sensor bias).
- **D (Derivative)**
  Reacts to how fast it is falling (damps oscillations).

Motor speed command is:

$$\text{Output} = K_p(\theta) + K_i \int \theta dt + K_d \frac{d\theta}{dt}$$

When PID is tuned well → robot stands straight.
If PID is wrong → robot shakes, oscillates, or falls instantly.

Dynamics of the System

A self-balancing robot is basically:

- A mass on top (battery + body)
- Wheels at the bottom
- Torque applied at wheels creates acceleration
- Body leans opposite to wheel motion

If the robot falls forward → motors must drive forward
If the robot falls backward → motors must drive backward

This is matching the reaction to the falling direction.

Overall System Flow

Here's the full logic:

1. Read accelerometer → compute accel angle
2. Read gyro → gyro angle integration
3. Complementary filter → final tilt angle
4. PID controller → motor output speed
5. Run motors to push robot back upright
6. Repeat 250–500 times/second (loop frequency)

What You Must Understand Before Building

By now you should know:

- Why accelerometer alone fails
- Why gyro alone fails
- Why complementary filter fixes everything
- Why PID is required
- How an inverted pendulum behaves
- How motors counter gravitational torque
- Why balancing requires constant correction
