Stability-Based Scale Estimation for Monocular SLAM

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Background

To enable autonomous robot navigation using monocular SLAM, accurate scale estimation is a critical requirement. Previous methods recover the scale by using additional metric sensors such as an IMU or a sonar altimeter. However, for small MAVs flying over an arbitrary ground structure, these sensors are often unreliable.

Objective

Solve the **scale ambiguity in monocular SLAM** without metric sensors, such as **IMU** or **sonar**.

Method

Theoretical analysis reveals a unique stability characteristics of **unscaled state feedback control** (Fig. 1).

We exploit this property to deduce the scale by **adaptively inducing and detecting vertical oscillations in hover.**

Contributions

1. We analytically show that when a proportional control system uses unscaled velocity feedback from monocular SLAM (Fig. 1), there is a **unique linear relationship** between the **absolute scale** of the SLAM system and the control gain at which instability arises, i.e., **critical gain** (Fig. 2).
2. We propose an **adaptive technique** to estimate the scale based on the hover stability of a quadotor MAV.

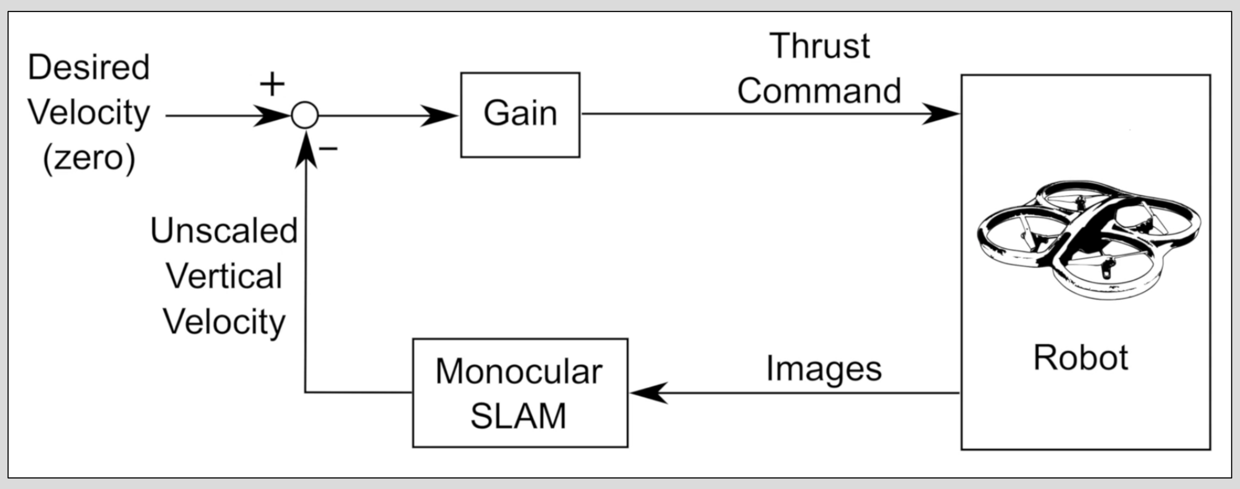
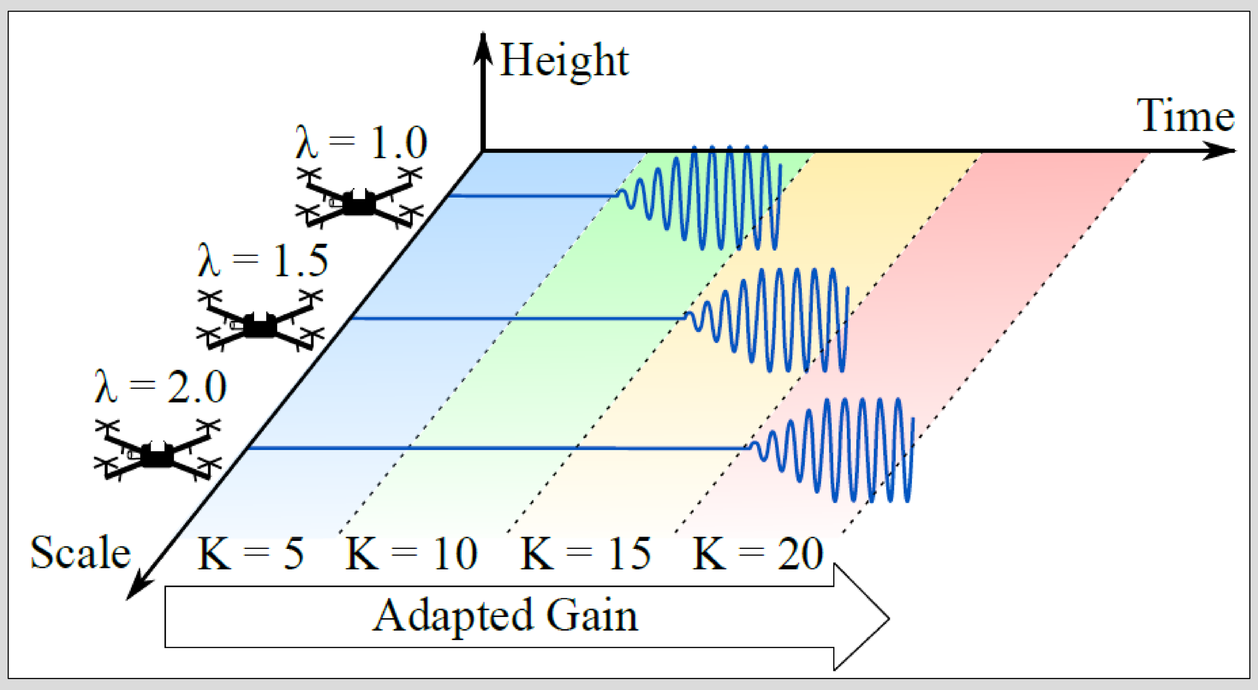


Figure 1. Unscaled Velocity Feedback Control



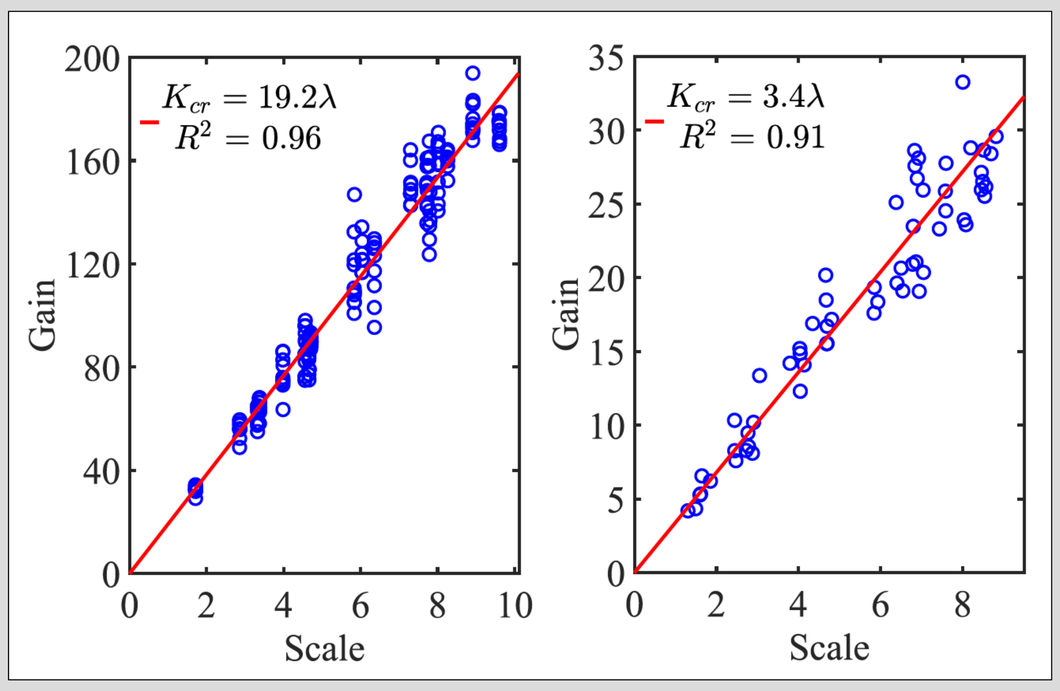
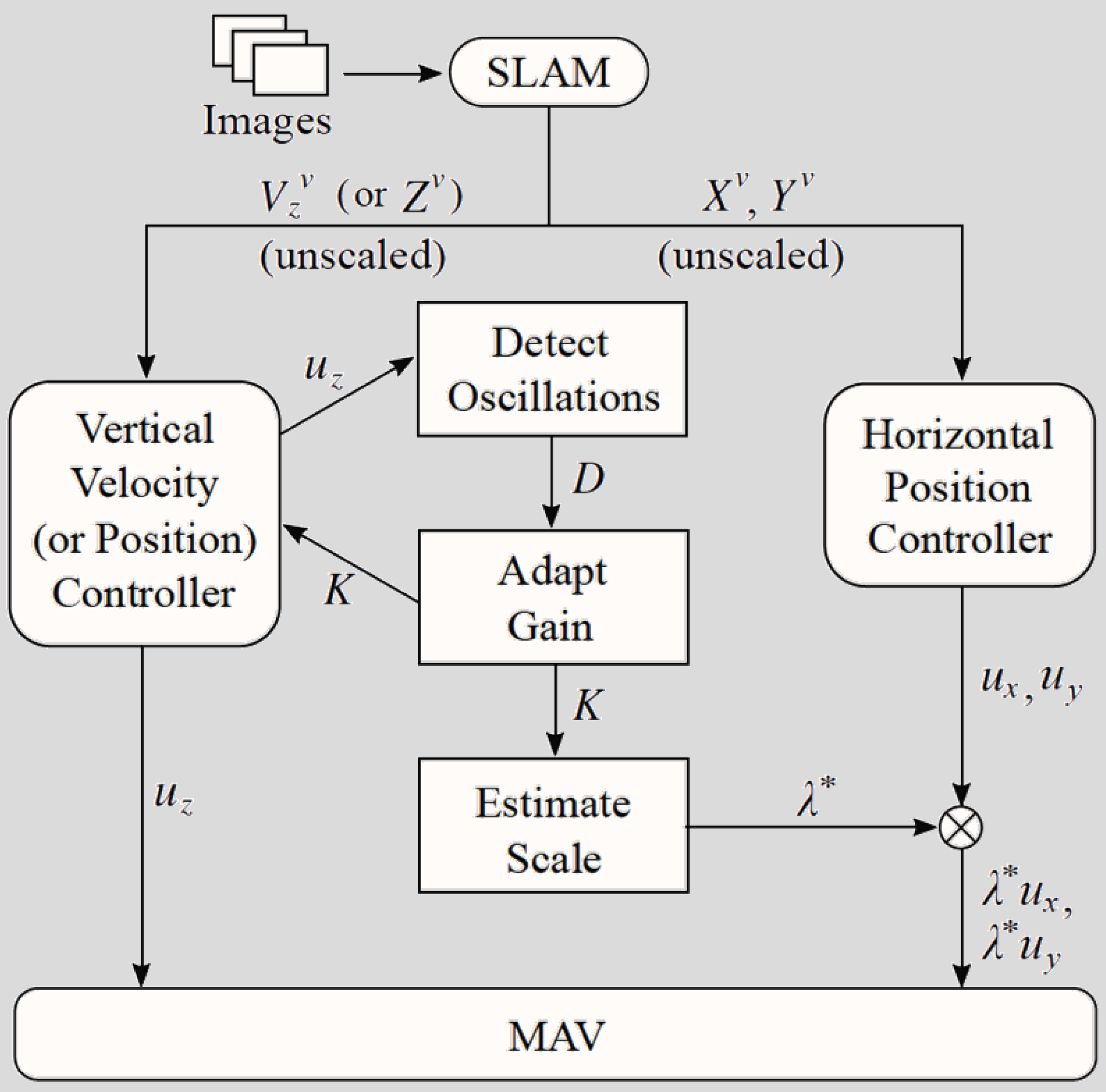


Figure 2. Linear relationship between the absolute scale and critical gain.
Left: Example illustration. Right: Verification through simulation and real-world experiments.

Adaptive Control



1. Detection of Self-induced Oscillations

We define a heuristic variable D as:

$$D(i, i_0, W) = \frac{1}{mW}\left(\max_{i' \in \{i_0, \cdots, i\}} \sum_{j=i'-W+1}^{i'} |u_z[j]|\right)$$

where m is mass, W is discrete time window size, and u_z is thrust signal. The onset of oscillations is detected when $D > D_{thr}$.

2. Adaptive Gain Control

$$K_{i+1} = K_i + PK_i\frac{(D_{thr} - D_i)}{D_i}$$

3. Iterative Scale Update for Horizontal Control

$$\lambda_i^* := \frac{K_i}{\alpha^*}$$

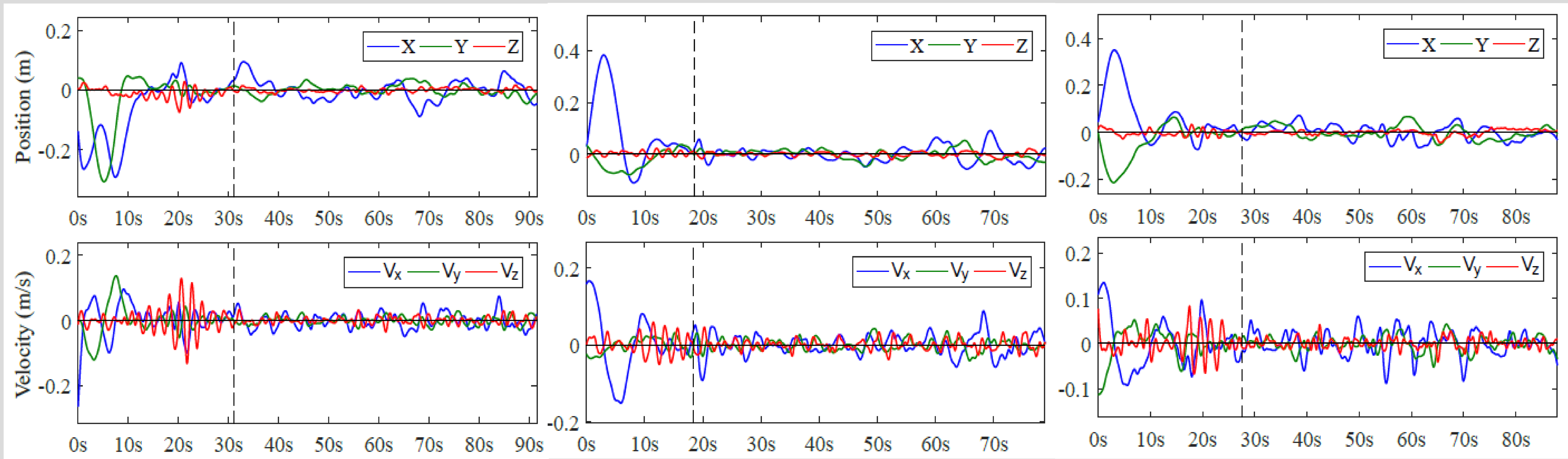
where α^* is to be empirically found in advance by performing a linear fit using the ground-truth.

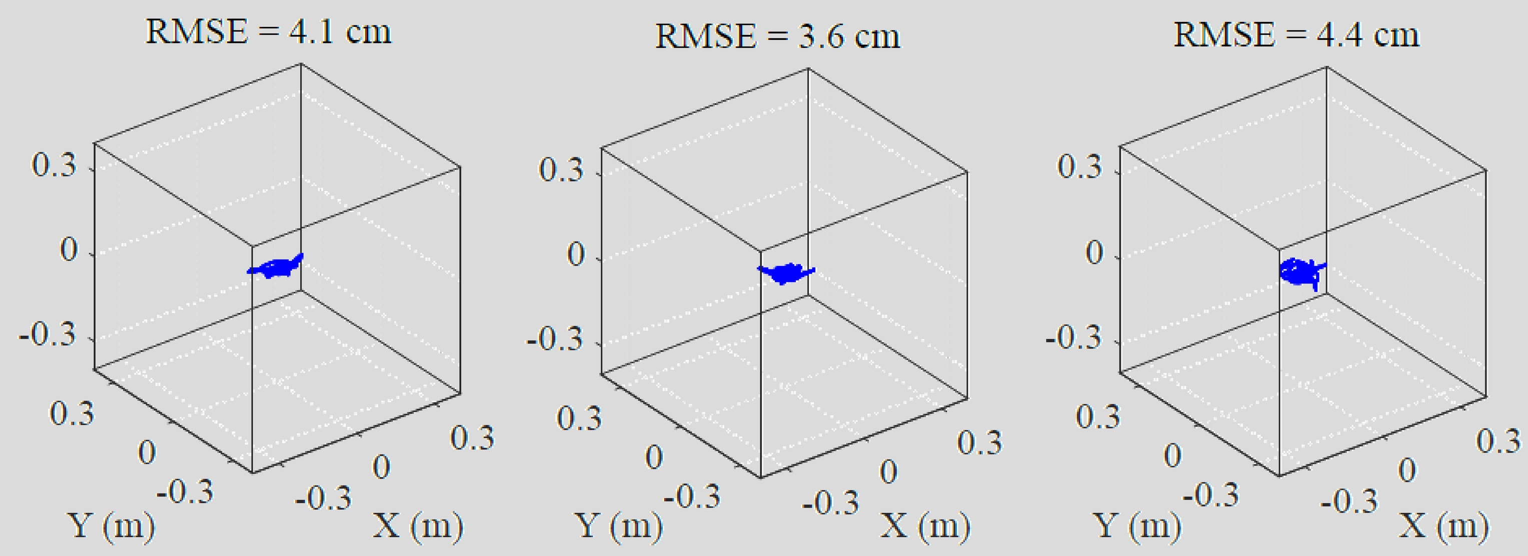
Results

1. Scale Estimation Accuracy:

Within the scene distance between 2m and 6m, the average scale estimation error is estimated to be **13.4%** and **16.0%** in simulation and in the real world, respectively.

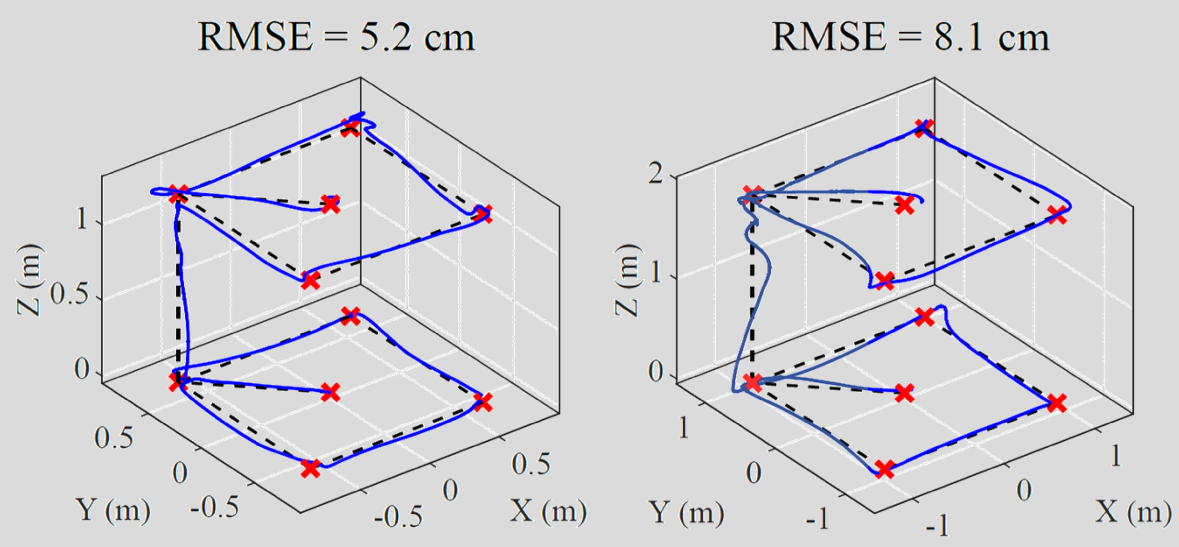
2. Hovering:





(a) Scene Distance = 2 m (b) Scene Distance = 4 m (c) Scene Distance = 6 m

3. Figure Flying



4. Waypoint Following

Target (x, y, z) (m)	$(0, 0, 2)$	$(0, 2, 0)$
Convergence time (s)	5.4 ± 0.9	2.7 ± 0.2
Peak speed (m/s)	0.86 ± 0.05	1.13 ± 0.05

5. Video Demo

We demonstrate hovering, figure-flying and 10m straight line following with Parrot AR.Drone.