Impedance Tuning Guide

This guide describes a practical procedure for tuning the virtual spring–damper impedance layer implemented by `MarsImpedance` on the Teensy 4.1 hexapod.

The impedance layer sits on top of the existing trajectory + PID controllers and adds a compliant "springy" behavior in joint space or simple Cartesian Z-space.

- **Joint mode**: per-joint virtual springs and dampers.
- **Cartesian mode**: Z-axis (vertical) impedance at the foot, mapped into tibia correction.

All tuning is performed at runtime over the serial command interface using the `IMP` command family.

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1. Concepts and knobs

1.1 Modes

- `IMP MODE OFF`
  Impedance disabled. Only base trajectory and PID act on the joints.
- `IMP MODE JOINT`
  Per-joint impedance around the commanded joint angles.
- `IMP MODE CART`
  Cartesian (foot) impedance, currently applied along the body-frame Z axis and mapped into the tibia joint.

Impedance is globally gated by `IMP ENABLE` / `IMP DISABLE` and the `imp.enabled` config flag.

1.2 Joint-space gains

Commands:

- `IMP JSPRING <COXA|FEMUR|TIBIA|ALL> <milli>`
- `IMP JDAMP  <COXA|FEMUR|TIBIA|ALL> <milli>`

These adjust per-joint spring and damping gains in **milli-units** (integers). Larger values mean:

- Higher `JSPRING` → stiffer response to joint position error (more "springy").
- Higher `JDAMP` → stronger resistance to joint velocity (more "viscous").

Gains can be set per joint or for all three at once using `ALL`.

1.3 Cartesian Z gains

Commands:

- `IMP CSPRING <Z|ALL> <milli>`
- `IMP CDAMP  <Z|ALL> <milli>`

These adjust spring and damping along the body-frame vertical axis at the foot. The implementation currently uses only Z; `ALL` sets the same value on X/Y/Z for future expansion, but X/Y are effectively unused in Phase 1.

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2. Pre-flight checks

Before tuning impedance:

1. **PID must be stable**
   - Tripod test mode should not oscillate badly.
   - Single-leg PID tests should show monotone or mildly underdamped behavior.
2. **No persistent safety errors**
   - STATUS should not show streaming soft-limit, collision, or temperature lockouts for a static stance.
3. **Start with impedance OFF**
   - `IMP DISABLE`
   - `IMP MODE OFF`
   - Verify `[IMP]` in `STATUS` reports `enabled=0` or `mode=off`.

It is strongly recommended to start with the robot supported (e.g., body on a stand, feet free) while you find initial gains.

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3. Joint-space impedance tuning

3.1 Baseline configuration

1. Enable impedance but set all gains to zero:
   - `IMP ENABLE`
   - `IMP MODE JOINT`
   - `IMP JSPRING ALL 0`
   - `IMP JDAMP  ALL 0`
2. Confirm in `STATUS` that `mode=joint` and all joint gains are 0.
3. Place the robot in a comfortable stance with the legs supported or hanging so they can be safely disturbed by hand.

3.2 Tibia tuning (vertical compliance)

The tibia has the most direct effect on vertical foot motion. Tune it first.

1. **Single-leg test**

- Choose one leg (e.g., LF) and keep the robot otherwise supported so tipping is impossible.

2. **Introduce small tibia gains**
   - Start very soft:
     - `IMP JSPRING TIBIA 200`
     - `IMP JDAMP   TIBIA  50`
   - Manually move the tibia (lift/lower the foot) and release.
3. **Adjust spring (JSPRING)**
   - Increase in small steps (e.g., +100–200 at a time):
     - If the leg feels **floppy** and does not return noticeably toward its original angle, increase `JSPRING`.
     - If the leg snaps back aggressively or the servo sounds strained, reduce `JSPRING`.
4. **Adjust damping (JDAMP)**
   - For a given `JSPRING`:
     - If the leg **overshoots and bounces**, increase `JDAMP`.
     - If the leg feels **sluggish or sticky**, decrease `JDAMP`.

A good tibia target for initial testing is typically in the **low-thousands** for `JSPRING` and **20–50% of that value** for `JDAMP`.

Acceptance for tibia:

- When you pull the foot down and release, it returns smoothly toward nominal height.
- One small rebound is acceptable; sustained or growing oscillation is not.

3.3 Femur tuning (vertical + pitch compliance)

Femur impedance affects both vertical stiffness and body pitch.

1. Reset femur gains:
   - `IMP JSPRING FEMUR 0`
   - `IMP JDAMP   FEMUR 0`
2. With tibia gains fixed, add small femur gains:
   - `IMP JSPRING FEMUR 200`
   - `IMP JDAMP   FEMUR  50`
3. Push down on the body near the leg and release.
4. Increase/decrease `JSPRING FEMUR` and `JDAMP FEMUR` as needed:
   - Too bouncy: increase damping or reduce spring.
   - Too rigid: reduce spring to avoid large torques and pitch shocks.

Acceptance for femur:

- Pressing the body down causes a controlled sink and recovery.
- No multi-cycle pitch oscillation when you let go.

3.4 Coxa tuning (lateral/yaw compliance)

Coxa motions affect lateral sway and yaw. They should usually be softer than femur/tibia.

1. Start very small:
   - `IMP JSPRING COXA 100`
   - `IMP JDAMP   COXA  30`
2. Gently push the hip sideways or twist the body around the vertical axis.
3. Adjust:
   - If the robot pivots back sharply or oscillates side-to-side, reduce coxa spring and/or increase damping.
   - If it feels completely dead sideways, increase spring slightly.

Acceptance for coxa:

- Lateral pushes result in mild sway and a slow recentering.
- No obvious side-to-side ringing.

3.5 Whole-robot sanity check

Once per-joint gains feel good:

1. Try a **slow tripod gait** (test mode).
2. During walking:
   - Lightly nudge the body and individual legs.
   - Watch for:
     - Stable foot placement.
     - No violent corrections.
     - No high-frequency chatter.

If gait becomes unstable when impedance is enabled, scale all joint gains down (e.g., halve JSPRING/JDAMP) and revisit.

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4. Cartesian Z impedance tuning

After JOINT mode is working, you can experiment with CART mode to shape vertical compliance at the foot.

4.1 Initial CART configuration

1. Set mode and small Z gains:
   - `IMP ENABLE`
   - `IMP MODE CART`
   - `IMP CSPRING Z  500`
   - `IMP CDAMP   Z  100`

2. Confirm in `STATUS` that `mode=cart` and only Z gains are non-zero.

4.2 Vertical push test

1. With the robot in a static stance, gently push the body vertically downward.
2. Observe:
   - The body should sink slightly then return.
   - Foot-ground contact should feel more compliant than in pure PID mode.
3. Adjust gains:
   - If too soft (body drops excessively and feels mushy): increase `CSPRING Z`.
   - If it bounces in height: increase `CDAMP Z` and/or reduce `CSPRING Z`.

Acceptance for CART Z:

- Body height recovers without repeated bouncing.
- No obvious high-frequency tibia chatter at standstill.

4.3 Gait with CART mode

1. Run the tripod test gait at conservative parameters.
2. Watch for:
   - Smooth absorption of small terrain changes.
   - No large heave oscillations (body bobbing up and down).

If gait degrades compared to JOINT mode, treat CART mode as experimental and either:

- Reduce CSPRING/CDAMP; or
- Revert to JOINT mode for production and use CART only for lab experiments.

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5. Heuristics and troubleshooting

5.1 Safe tuning order

1. Verify PID stability.
2. Tune JOINT impedance:
   - Tibia → Femur → Coxa.
3. Verify gait with JOINT impedance.
4. Experiment with CART Z impedance last.

5.2 Typical issues and remedies

- **Buzzing at standstill**
  - Gains too high or damping too low.

  - Reduce JSPRING/CSPRING or increase JDAMP/CDAMP.
- **Robot feels rigid and harsh**
  - Spring too high relative to base PID.
  - Lower JSPRING/CSPRING until manual pushes result in noticeable but controlled motion.
- **Gait destabilizes when impedance is enabled**
  - Scale all impedance gains down (e.g., multiply by 0.5).
  - Optionally reduce gait aggressiveness (step height/length) while tuning.
- **Feet don't track commanded pose well**
  - Gains may be too low (overly soft) or PID may be under-tuned.
  - Confirm PID-only tracking first, then add modest impedance.

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6. Example starting profiles

These are conservative starting points intended for lab testing, not final values.

6.1 Soft joint-space profile (stand + slow gait)

```
IMP ENABLE
IMP MODE JOINT
IMP JSPRING COXA  150
IMP JSPRING FEMUR 800
IMP JSPRING TIBIA 1200
IMP JDAMP   COXA  50
IMP JDAMP   FEMUR 200
IMP JDAMP   TIBIA 300
```

6.2 Experimental Cartesian Z profile

```
IMP ENABLE
IMP MODE CART
IMP CSPRING Z 800
IMP CDAMP   Z 200
```

Always adjust from these baselines in small steps and validate after each change.

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7. Persistence

When SD logging/config is enabled, `IMP` commands that change impedance parameters will be persisted back into `/config.txt` via `imp.*` keys, so your tuned gains survive reboot:

- `imp.enabled`

- `imp.mode`
- `imp.joint.k_spring_milli.[coxa|femur|tibia]`
- `imp.joint.k_damp_milli.[coxa|femur|tibia]`
- `imp.cart.k_spring_milli.z`
- `imp.cart.k_damp_milli.z`

Use `IMP LIST` and `STATUS` to confirm both runtime and persisted values match your expectations before field tests.