TinyMPC: Model-Predictive Control on Resource-Constrained Microcontrollers

Khai Nguyen, Sam Schoedel*, Anoushka Alavilli*, Brian Plancher, Zac Manchester*

REXLAB · Carnegie Mellon University Robotics Institute · Barnard College Columbia University · ICRA2024 YOKOHAMA | JAPAN

tinympc.org

Introduction

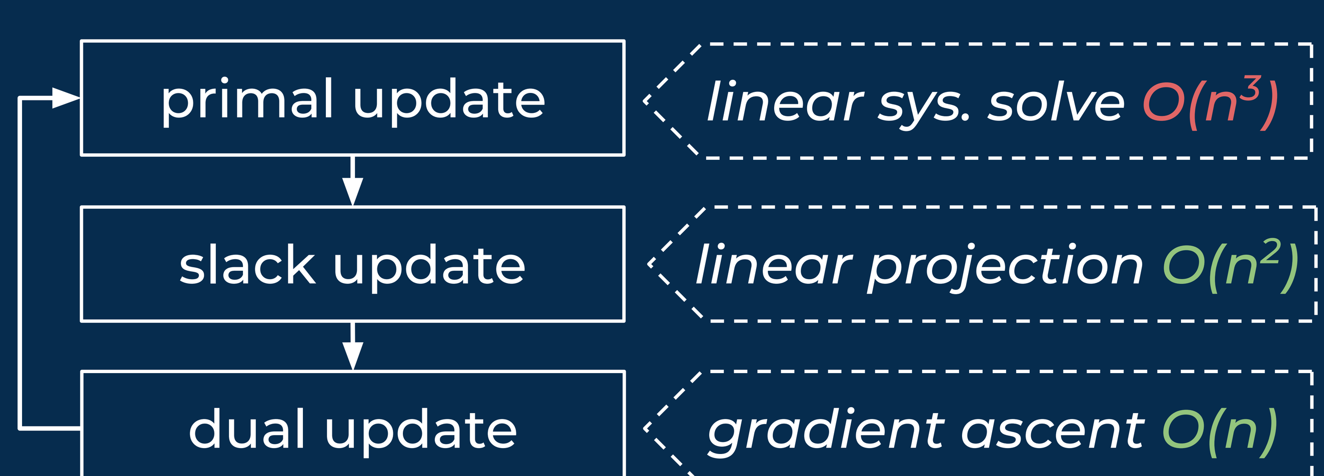
MPC enables safe and dynamic behaviors on complex robots but is computationally expensive.

Solving constrained optimization problems at real-time rates is challenging, even for large robots that carry more compute.

Can we bring MPC to compute-limited robots?

Algorithm

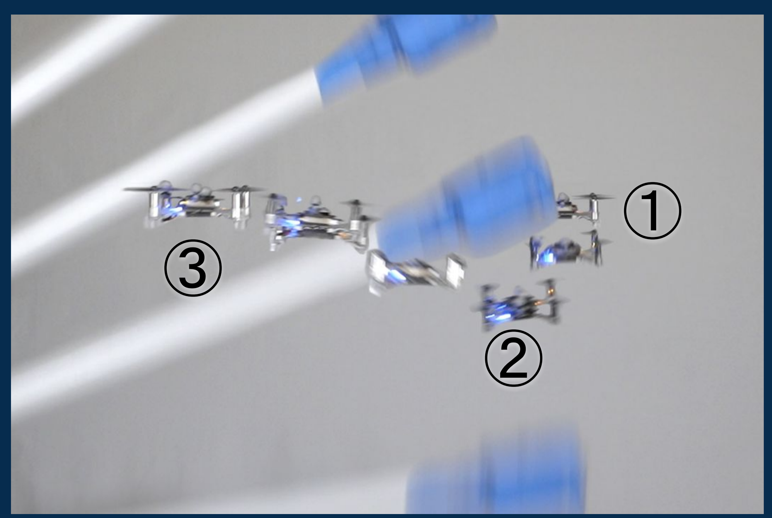
TinyMPC uses the Alternating Direction Method of Multipliers (ADMM), which iterates between solving three subproblems until convergence.



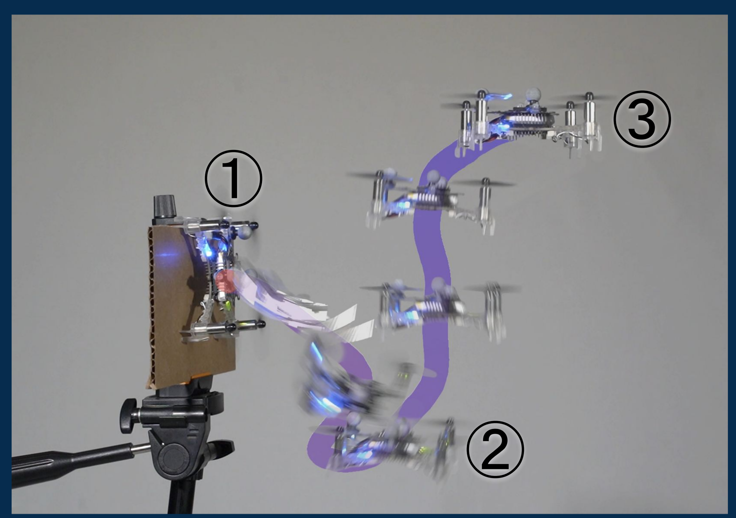
The primal update becomes a Linear-Quadratic Regulator, which has a closed-form solution (the Riccati recursion) that we exploit to reduce memory and online computation.

Hardware

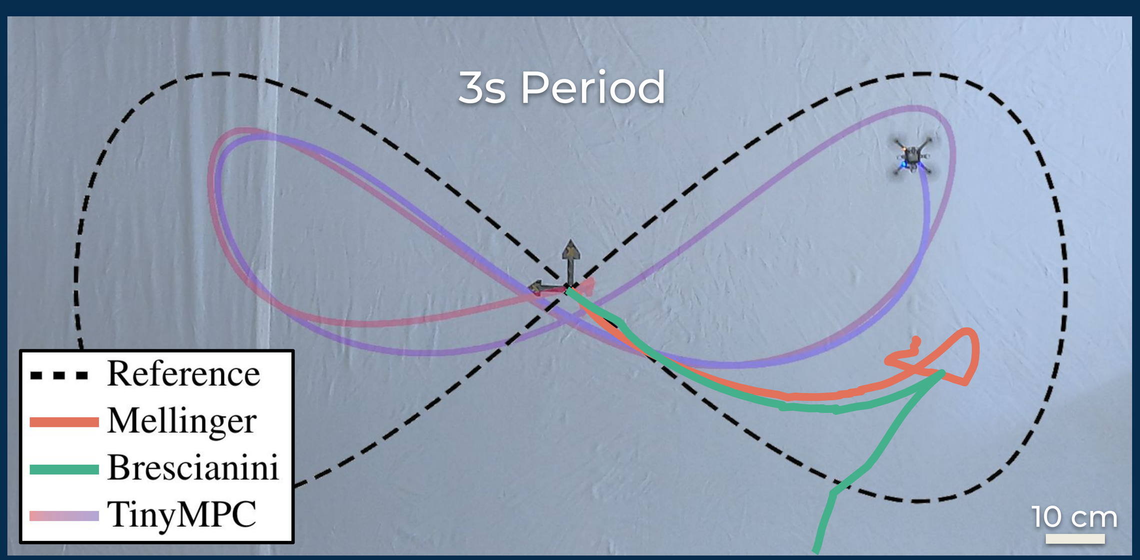
TinyMPC enables real-time optimal control onboard tiny robots like the Crazyflie 2.1, a 27 gram nano-quadrotor.



Dynamic obstacle avoidance



Extreme pose recovery



High-speed trajectory tracking

Key Ideas

Infinite-horizon LQR reduces memory footprint. Precomputation reduces online flop count.

1) We compute a single optimal gain matrix K and cost-to-go matrix P for the entire horizon.

$$K_k = (R + B^T P_{k+1} B)^{-1}(B^T P_{k+1} A) \xrightarrow{\infty} K_{\text{inf}}$$

$$P_k = Q + K_k^T R K_k + (A - BK_k)^T P_{k+1}(A - BK_k) \xrightarrow{\infty} P_{\text{inf}}$$

2) Precomputation of parts of the Riccati equations allows online computation of only matrix-vector products.

Offline

$$C_1 = (R + B^T P_{\text{inf}} B)^{-1}$$

$$C_2 = (A - BK_{\text{inf}})^T$$

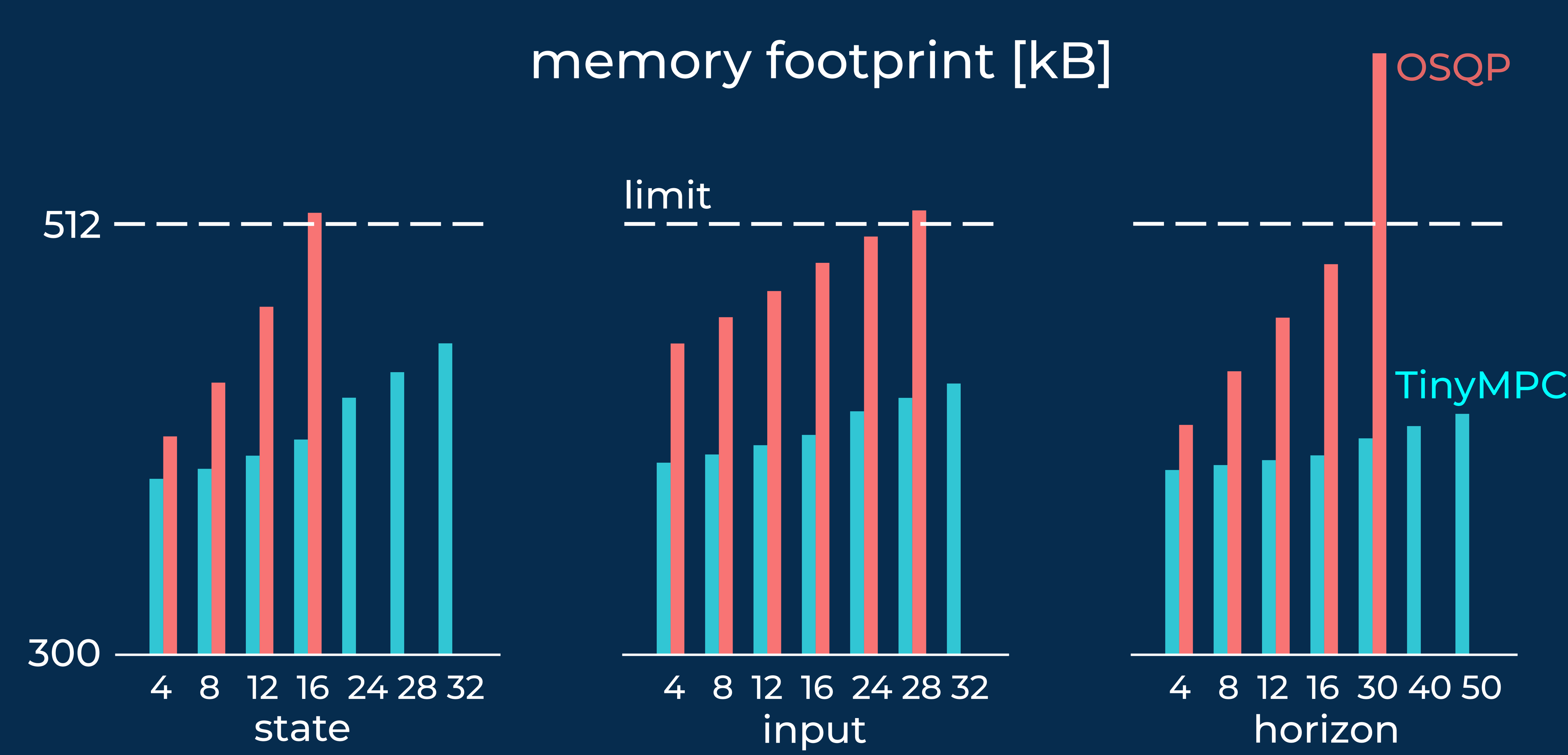
Online

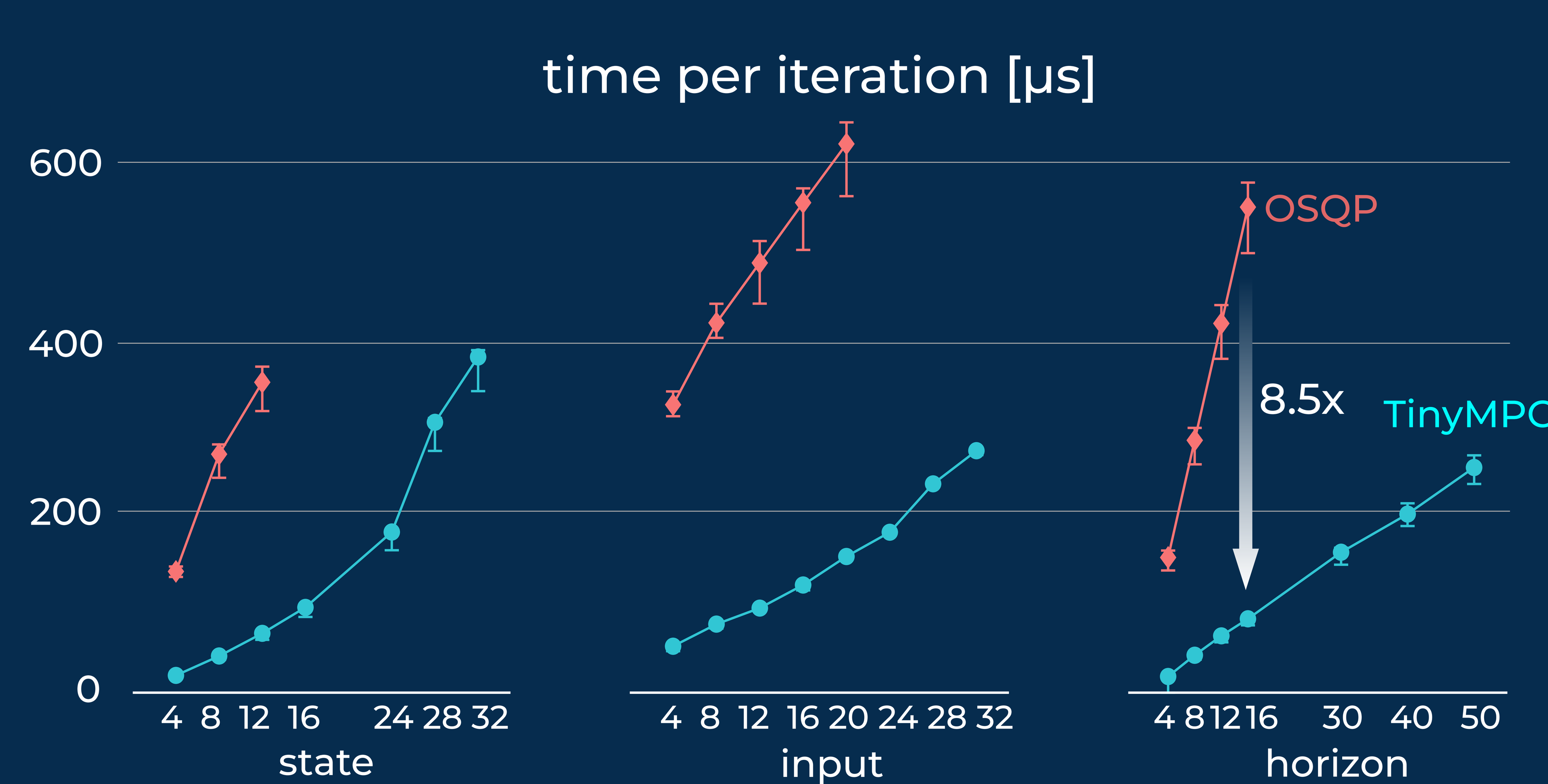
$$d_k = C_1(B^T p_{k+1} + r_k)$$

$$p_k = q_k + C_2 p_{k+1} - K_{\text{inf}}^T r_k$$

Benchmarks

We compared TinyMPC against OSQP, a state-of-the-art QP solver, on randomly generated convex MPC problems.





Microcontroller benchmarks were performed on a Teensy 4.1, which has 512 kB of RAM and a 600 MHz processor. Hardware demonstrations were performed on a Crazyflie 2.1, which has an STM32F405 processor running at 168 MHz with 192 kB of RAM.