

Background

In critically ill patients, deviations from normal blood pressure are associated with increased morbidity and mortality.

- Prolonged hypotension exacerbates end-organ ischemia and failure.
- Uncorrected hypertension can worsen intracranial hemorrhage and aortic dissection.

Blood pressure volatility and overcorrection may add new insults to existing injuries—for example, inducing hypotension in a patient with hemorrhagic stroke can cause brain ischemia, while aggressive blood pressure correction in hypotensive trauma can dislodge hemostatic clots and lead to further bleeding. The need for continuous, close monitoring by clinicians also absorbs valuable attention and resources.

To address these challenges, we developed a computational control algorithm for mean arterial pressure (MAP) regulation. By simulating infusion pump behavior and blood pressure, our algorithm automatically adjusts drug delivery to maintain MAP within physician-defined target ranges, reducing risks associated with error, delay, and volatility.

System Overview

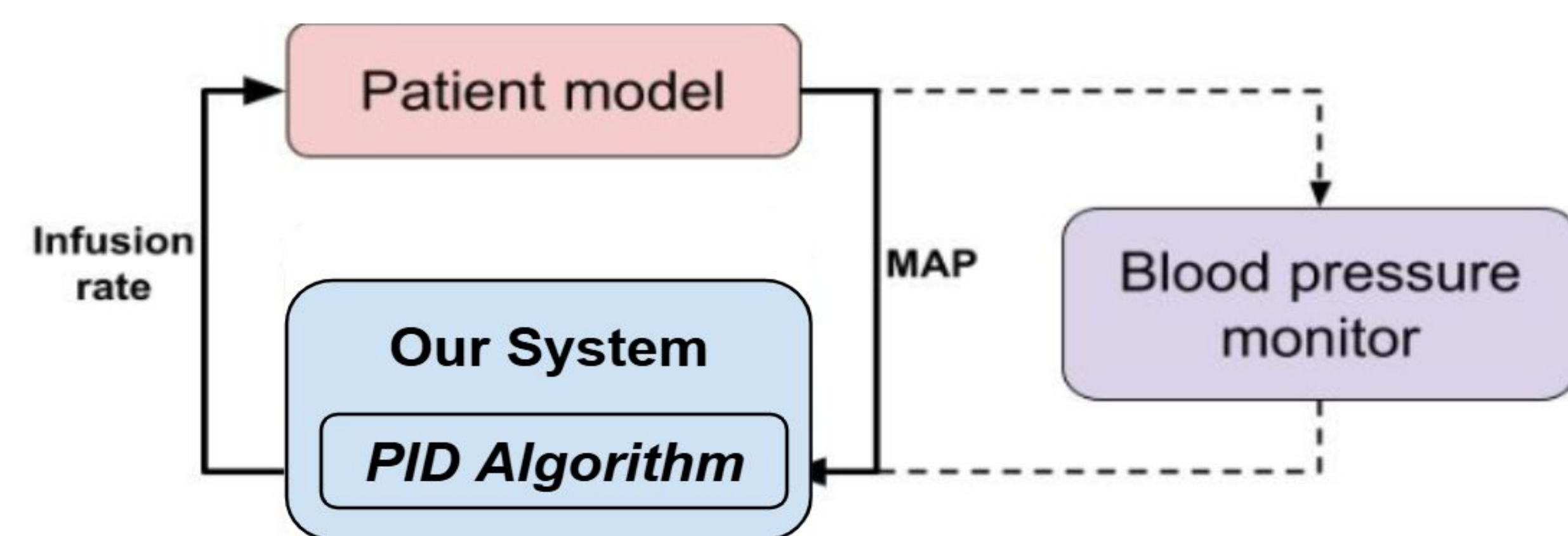
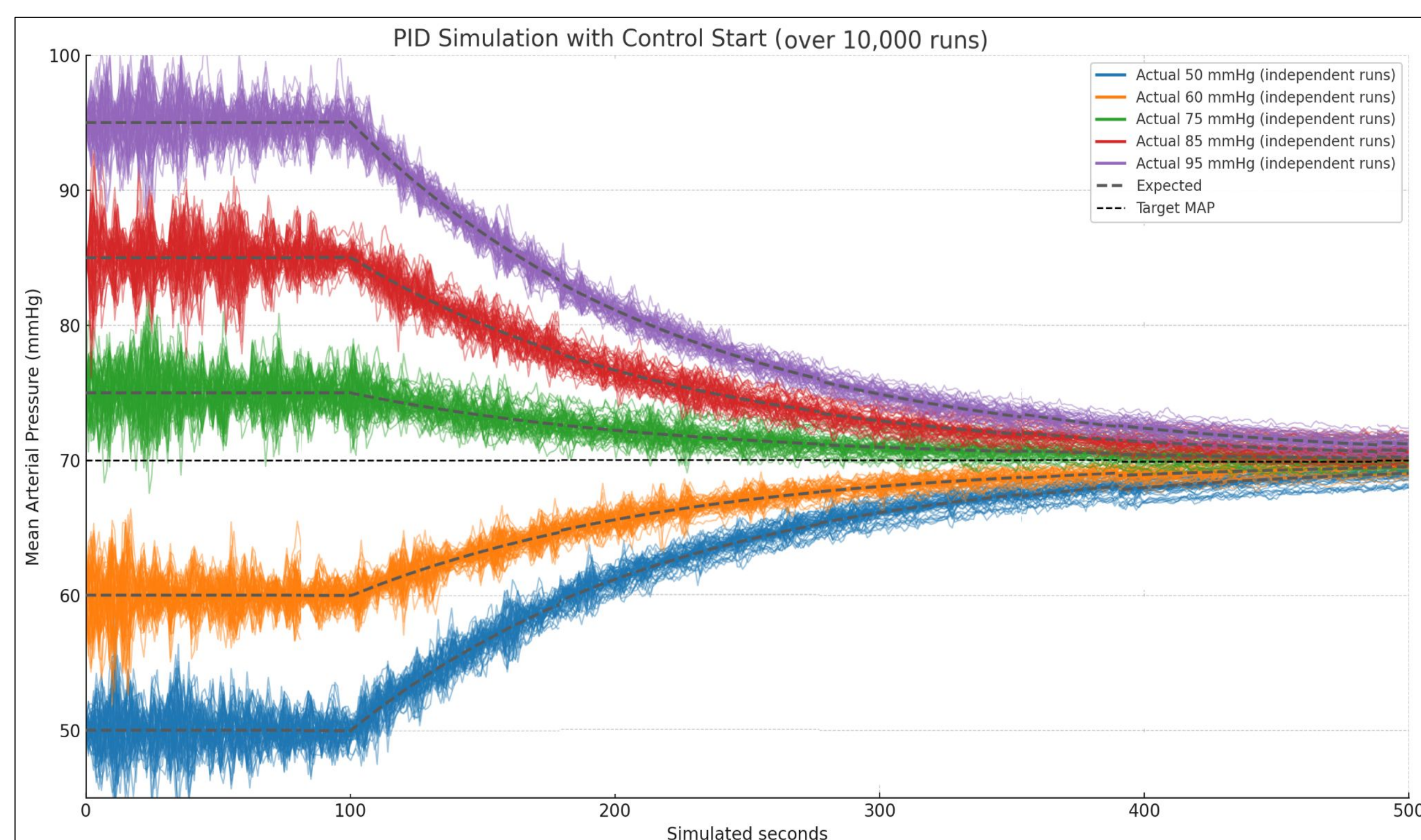


Figure 1: Feedback loop; calculates infusion rate based on MAP readings from patient model, further altering MAP

Results



Above: 10,000 simulations, 2000 each from 5 initial MAP conditions. After an initial 100 ss, the PID controller and moving target exponential curve are activated. From each initial MAP, tight control is rapidly achieved, following the moving target MAP. By 500 ss, all cohorts are near the final target MAP.

Methods

Simulation Framework

A model of patient MAP and its response to medication is used to test our system. The model takes the medication infusion rate as input, recursively calculates the current MAP using the previous MAP and infusion rates, and outputs the current MAP.

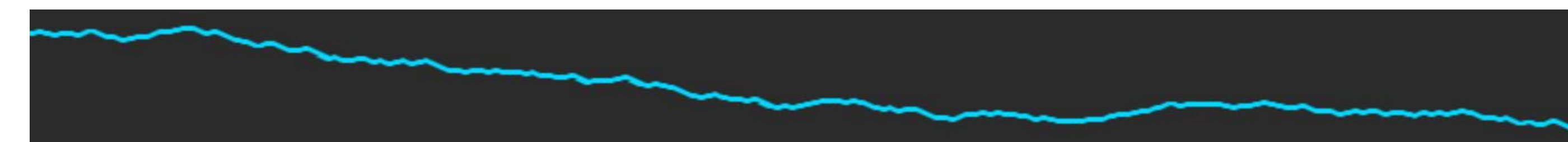


Figure 2: Waveform of simulated patient MAP over time

The simulation modeled MAP responses to drug infusion while accounting for physiological feedback delays, infusion rate constraints, and natural variability.

Phases:

- **0–100 simulated seconds (ss):** Baseline MAP is observed (no control algorithm implemented).
- **100–500 simulated seconds:** PID controller activated for MAP regulation.

In some instances, to test system responsiveness, two perturbations were introduced:

- **+20 mmHg hypertensive challenge** at 200 ss.
- **–20 mmHg hypotensive challenge** at 300 ss.

Collections of 10,000 simulations were performed across a range of initial MAP values from 50 to 95 mmHg, using a final target MAP of 70 mmHg.

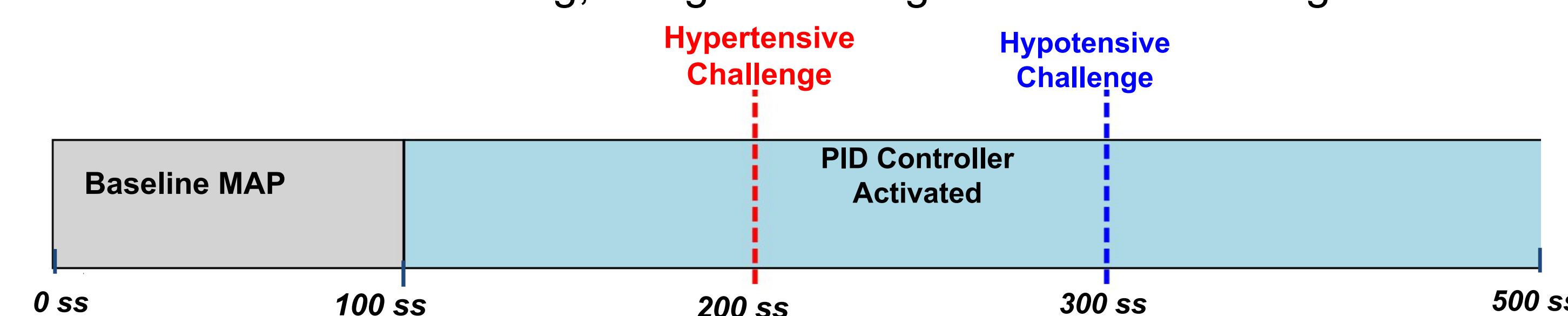


Figure 3: Simulation Timeline

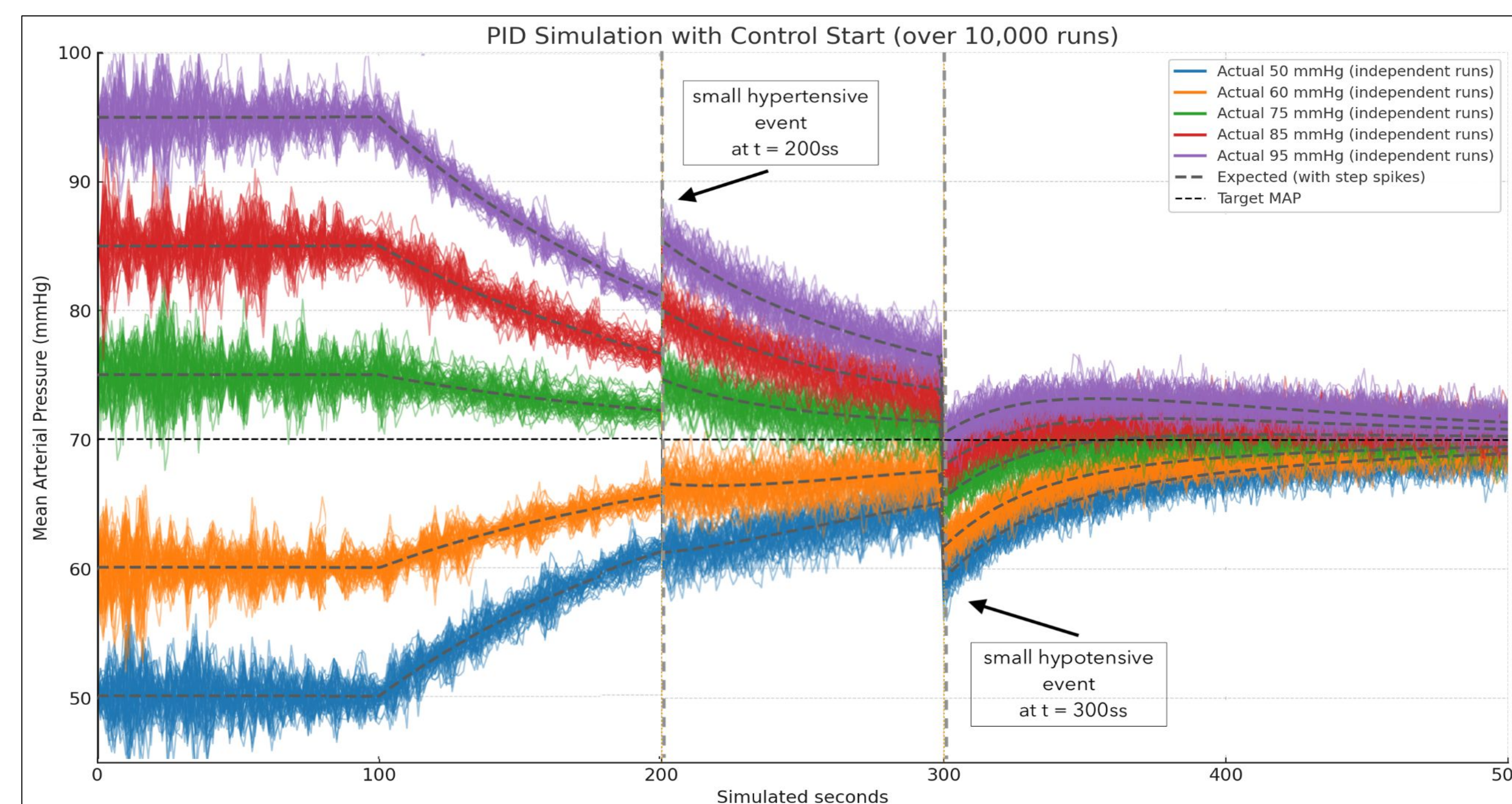
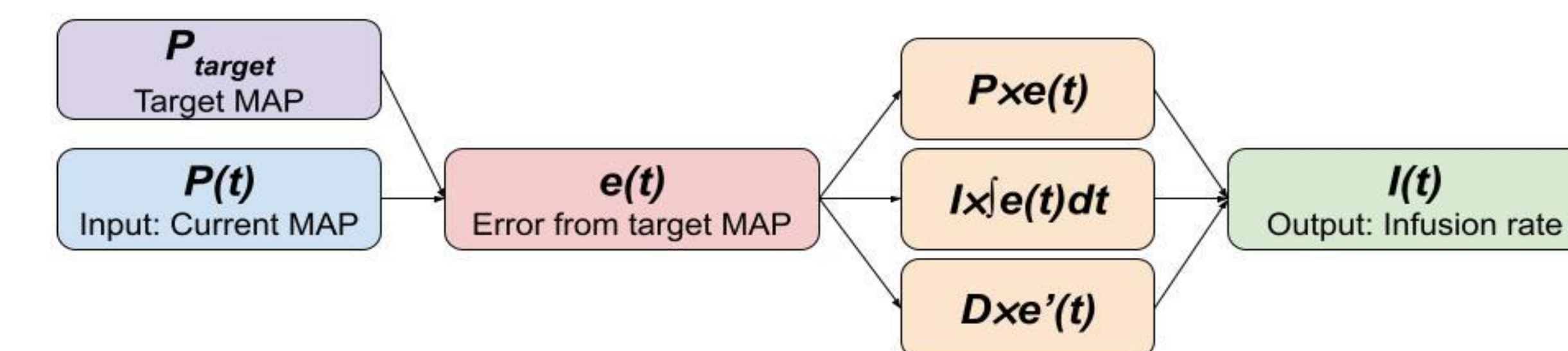


Figure 4: Flowchart of Our System's PID Algorithm

System Algorithm

Our system's algorithm employs a proportional integral derivative (PID) controller, taking the patient's MAP as an input, and outputting the medication infusion rate.

- **P (Proportional):** Responds immediately to error
 - error = current MAP – target MAP
- **I (Integral):** Corrects cumulative deviations, eliminating long-term offset
- **D (Derivative):** Anticipates changes and prevents overshoot by accounting for the rate of change



Rather than forcing the PID controller to immediately drive blood pressure to the final target MAP, we implemented a moving target model. The reference MAP follows an exponential decay curve that approaches the target over a fixed time scale (e.g., 60–90 s). This creates a gradually shifting setpoint that continuously guides the controller, producing smoother adjustments and minimizing abrupt changes. The result is a controlled, predictable correction that balances efficiency with patient safety and enables precise control of the time to reach the final target MAP

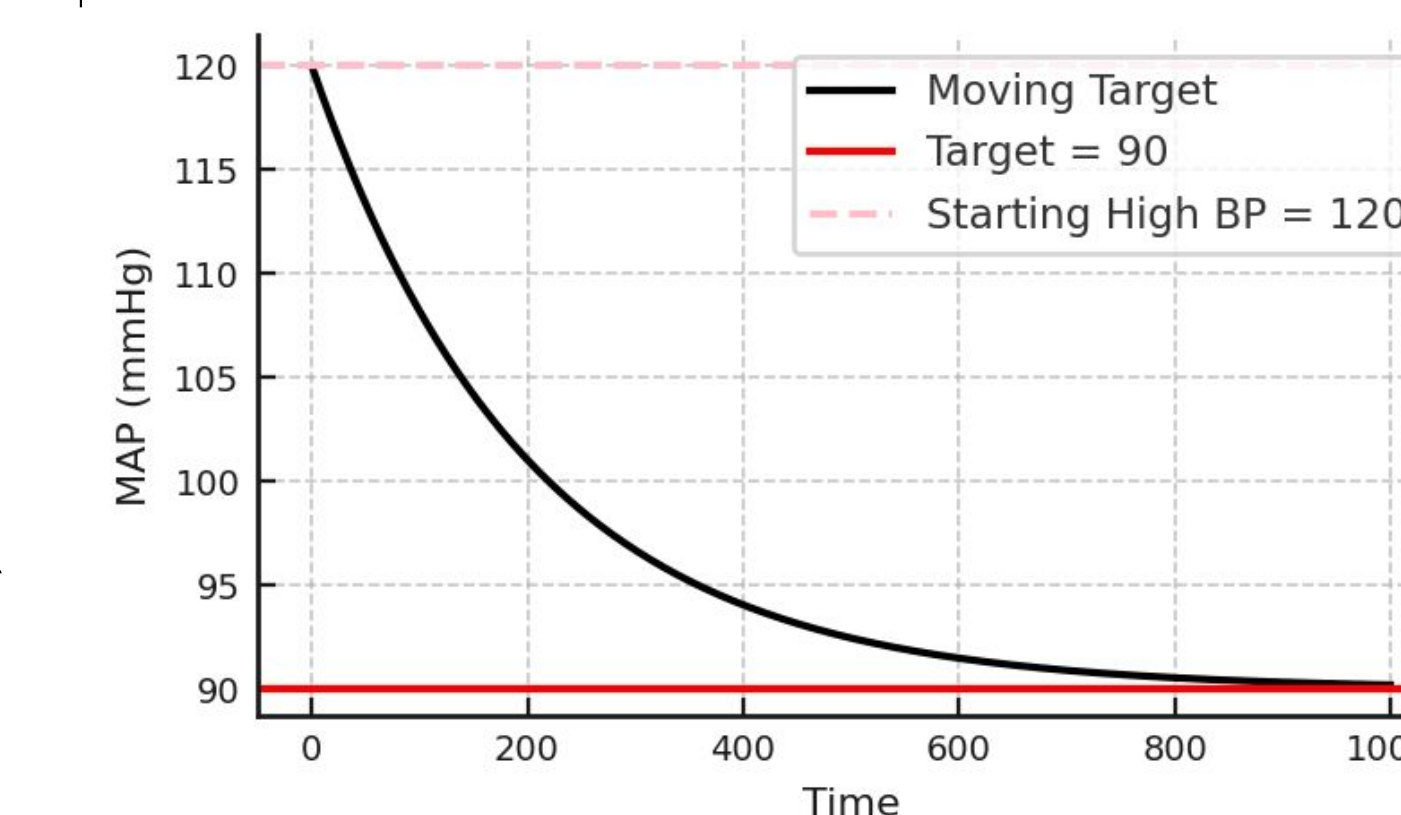


Figure 5: Moving target model provides smooth trajectory from initial MAP to final target.

$$\text{MAP}(t) = 30 \cdot e^{-0.0045t} + 90$$

In principal, any moving target (eg, exponential, linear, or other) could be selected to guide/augment the PID algorithm.

Conclusion

Our model thus demonstrates that this PID controller-based control algorithm provides rapid and stable MAP regulation, minimizing dangerous fluctuations during hypertensive and hypotensive events. The model allows efficient iteration of PID terms, moving target models, vasoactive drugs, and clinical scenarios.

References

1. Peixoto AJ. Acute Severe Hypertension. N Engl J Med 2019;381(19):1843-1852.
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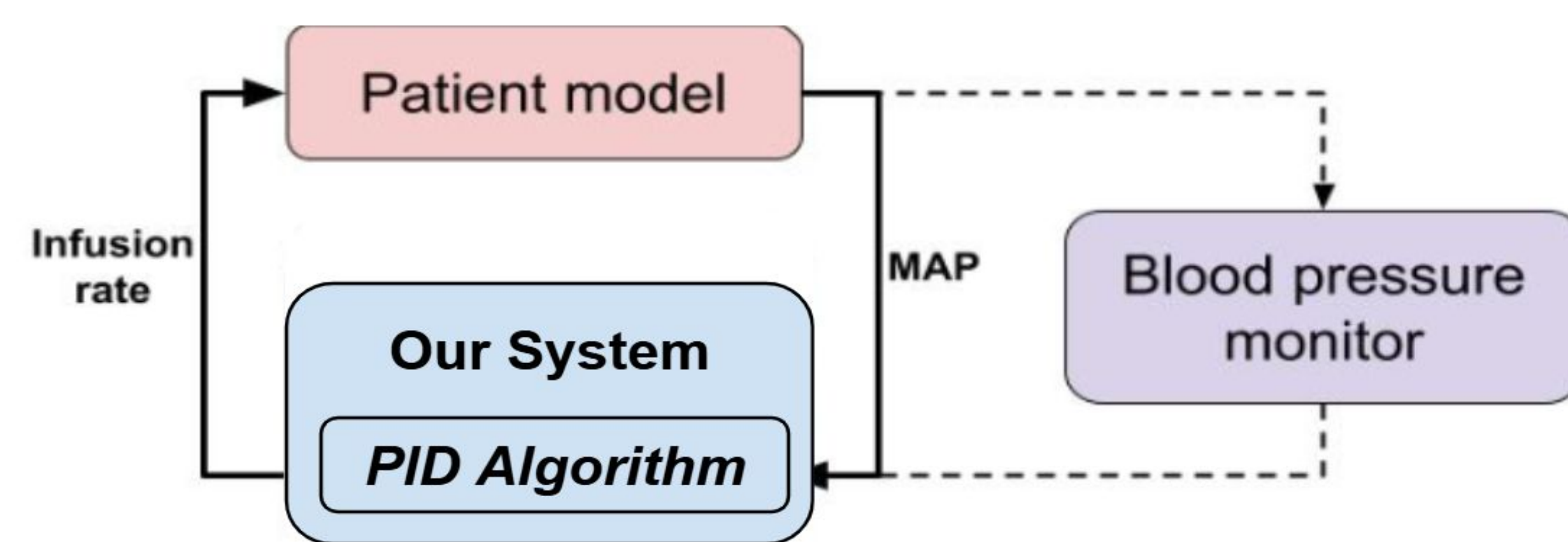


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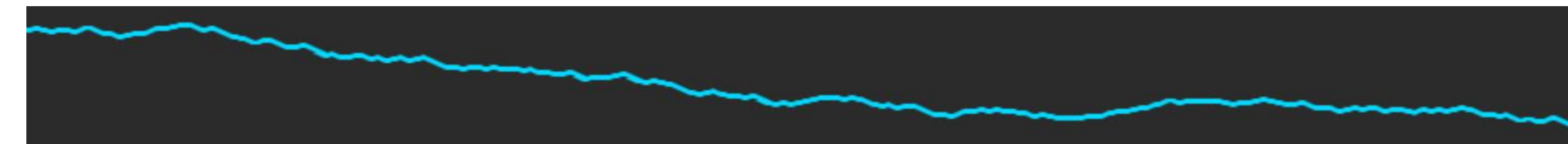


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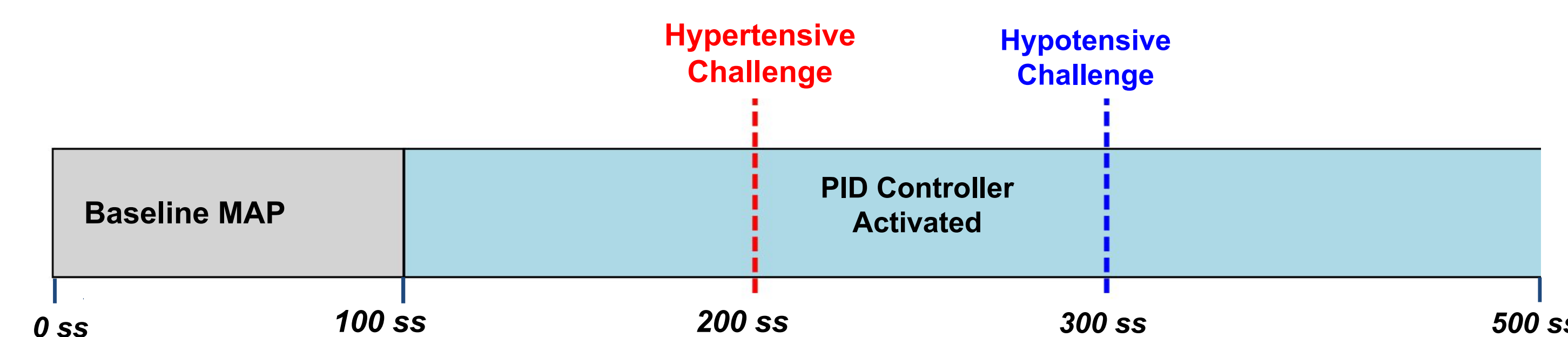


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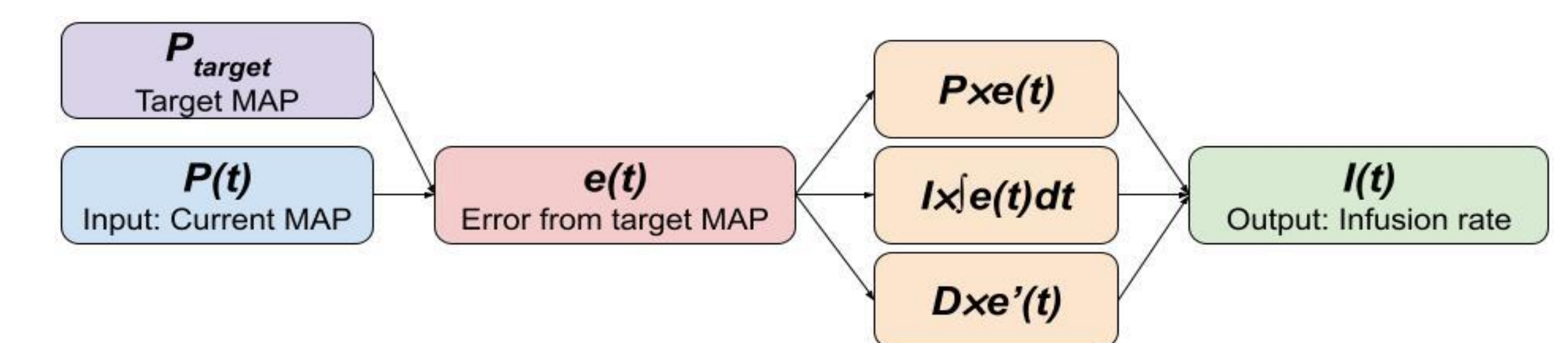


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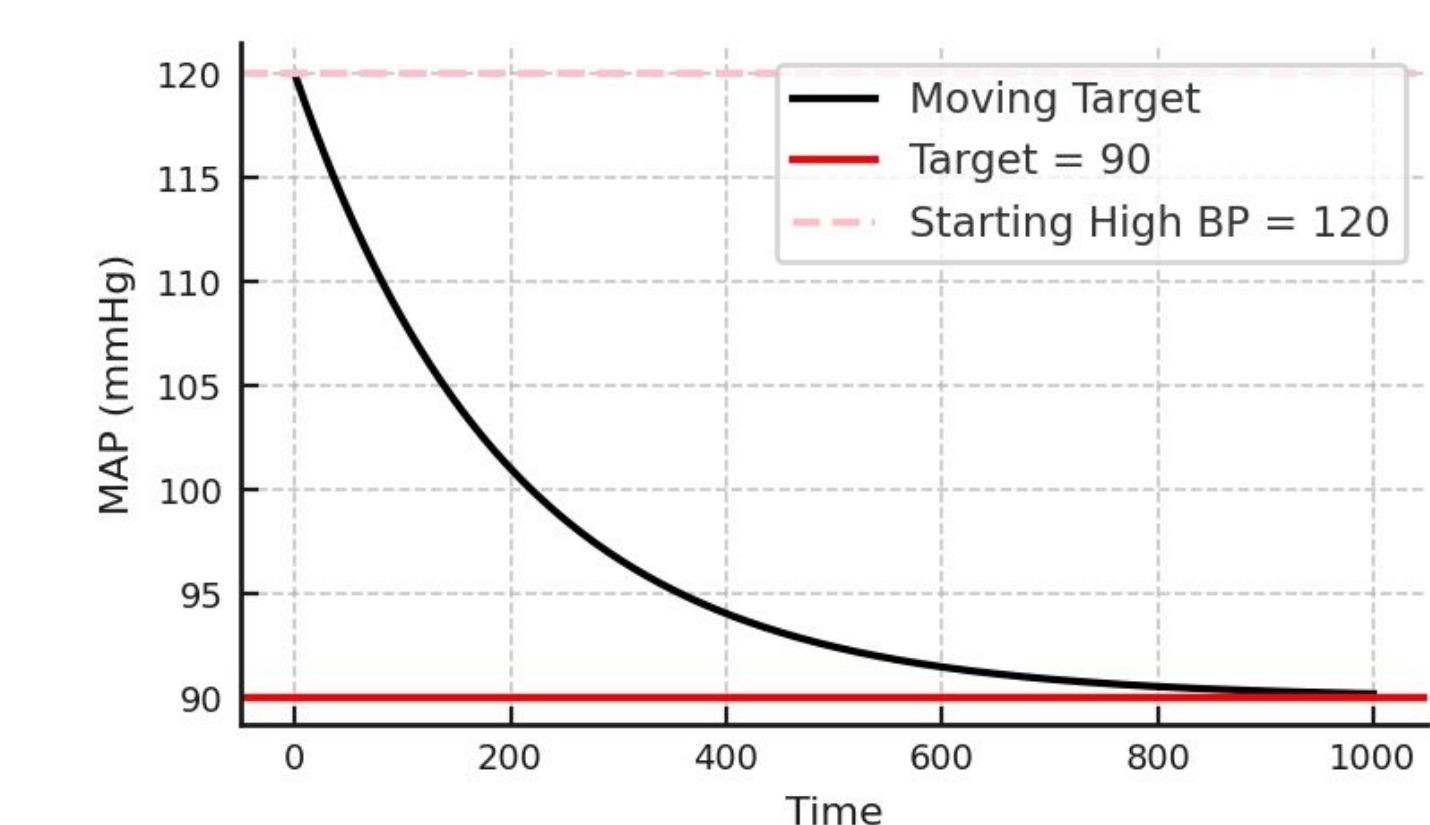
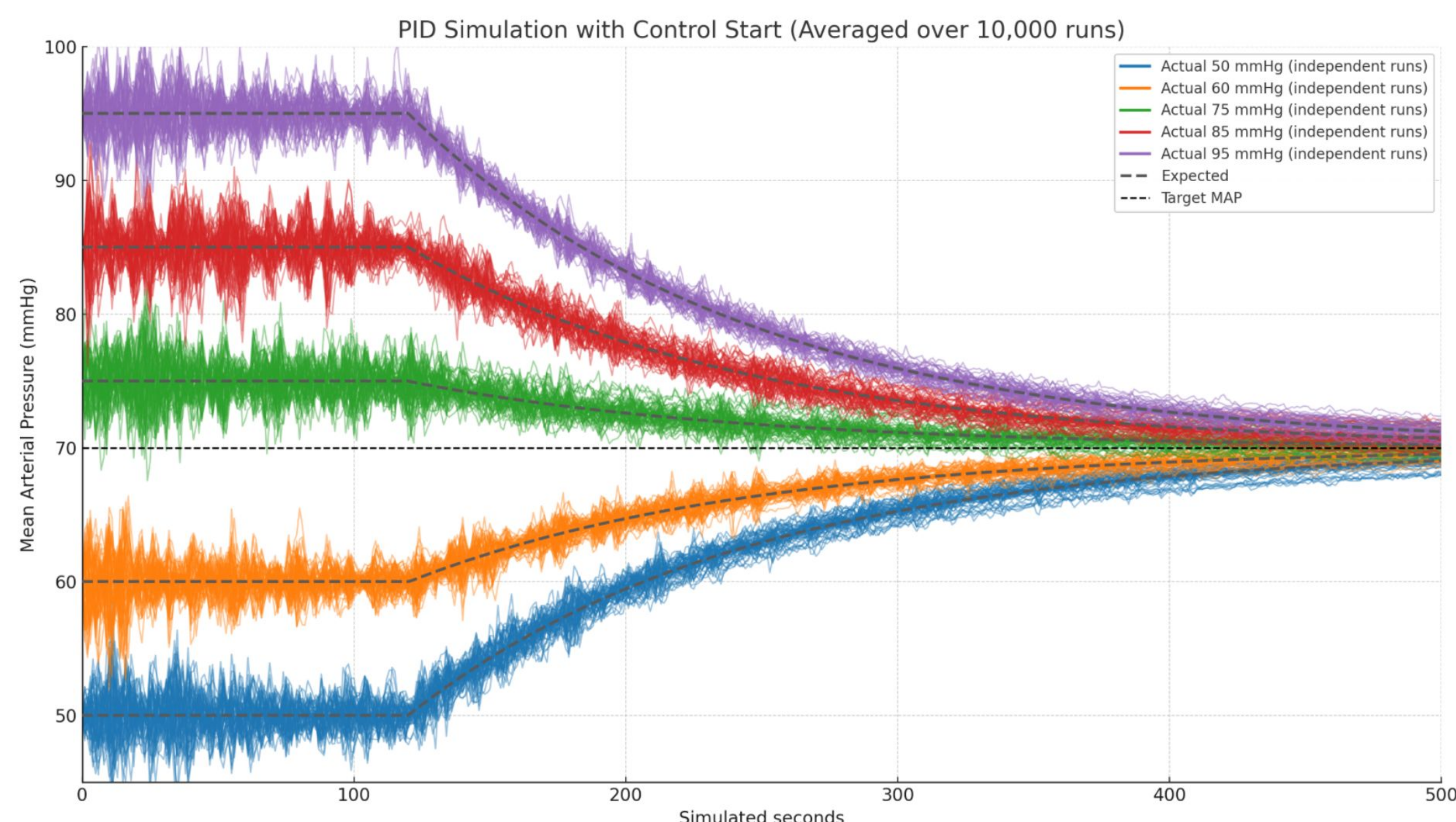


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Results



10,000 simulations completed in 22.6 simulated minutes (mean runtime of about 0.14 s per run)

The control system consistently achieved rapid stabilization: MAP reached the physician-defined target in mean ~68 ss

Once stabilized, MAP was maintained within ± 2 mmHg of target in 97% of simulations, demonstrating reliable long-term control.

The system recovered quickly from disturbances:

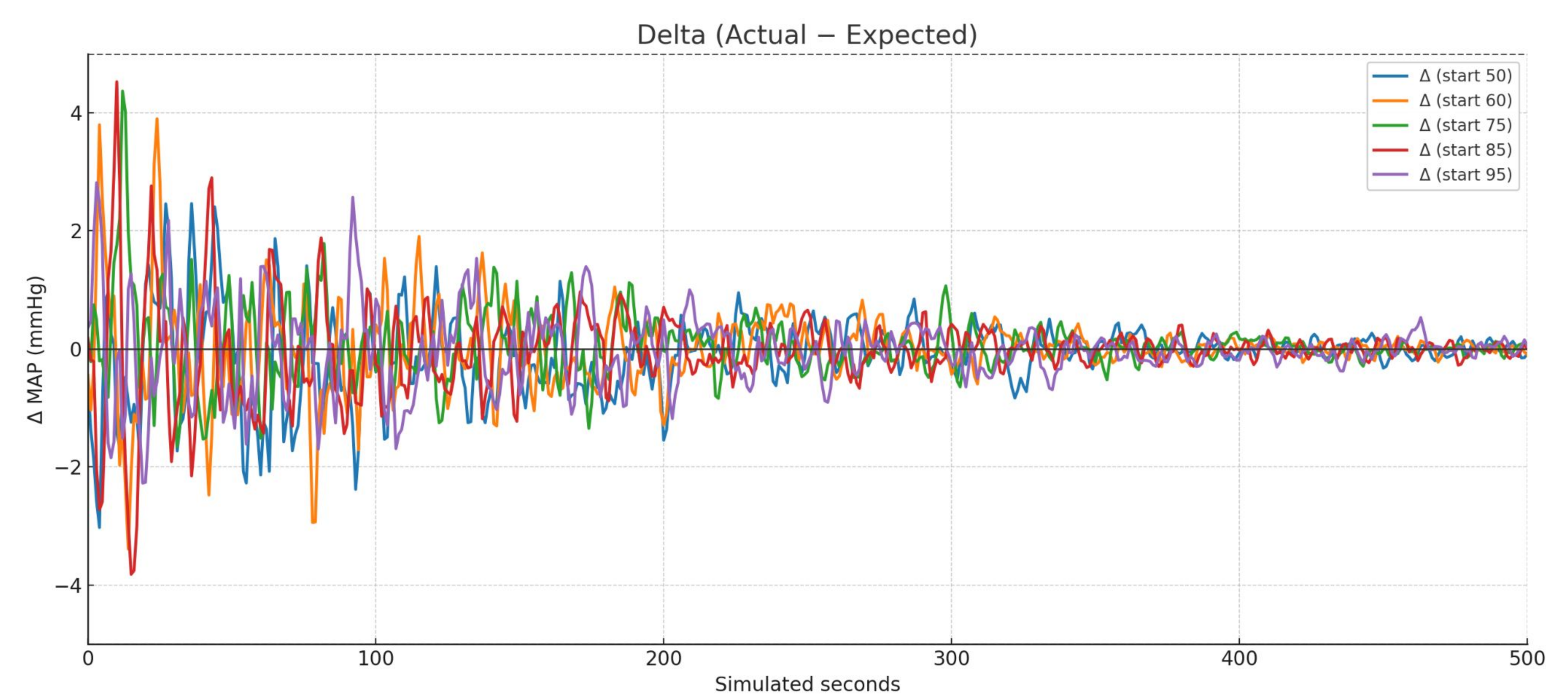
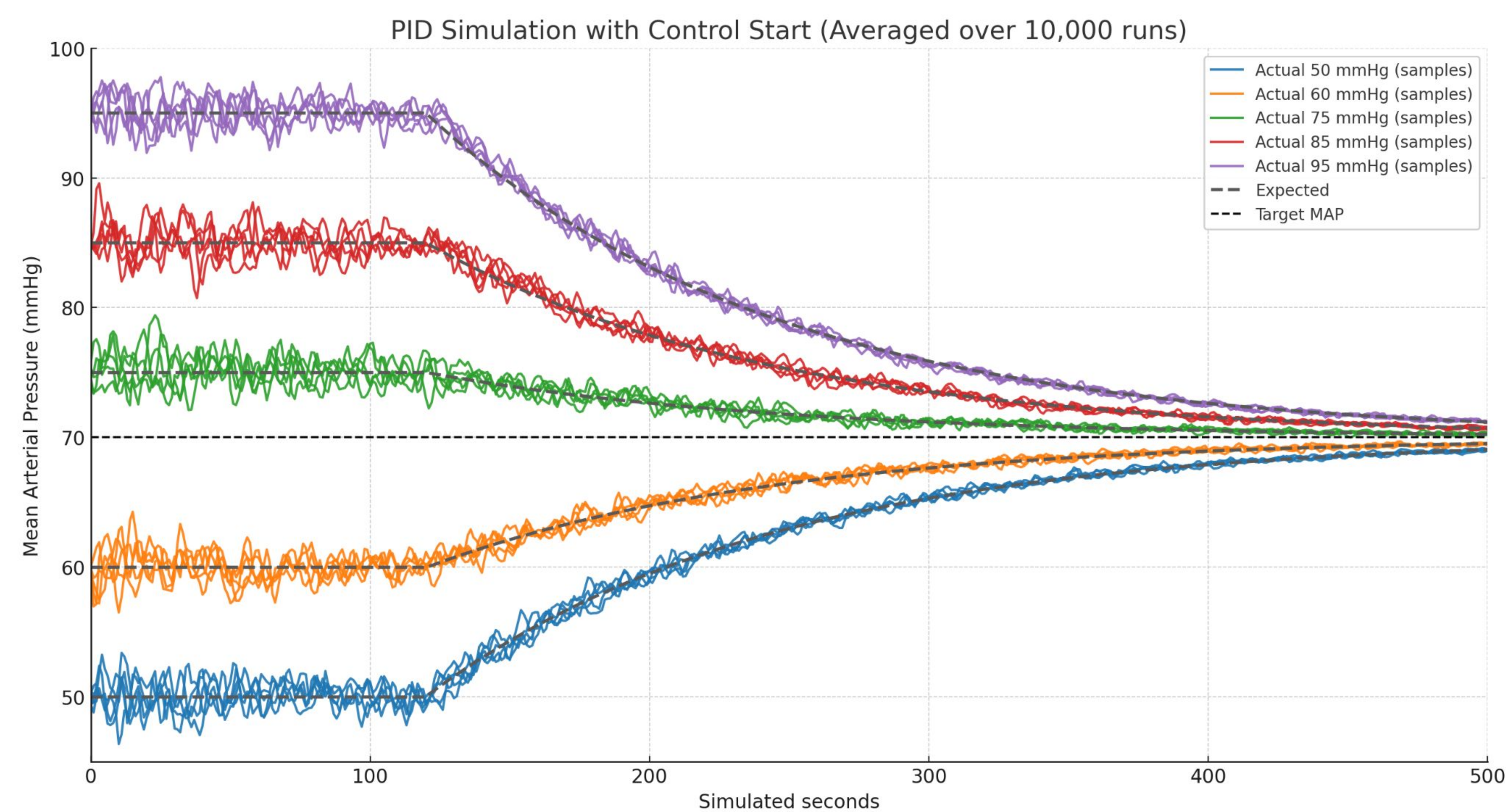
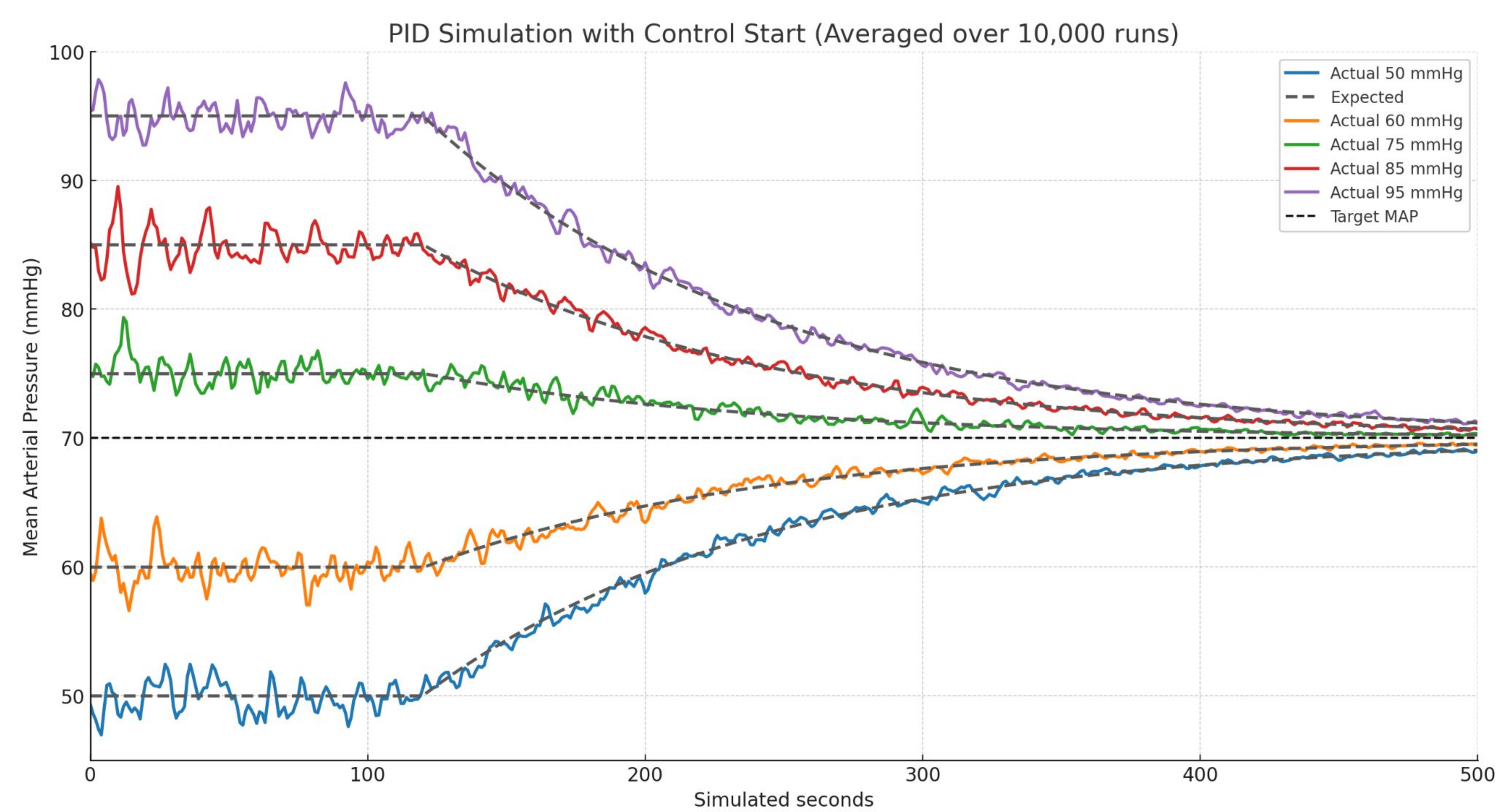
- **Hypertensive challenge (+20 mmHg):** Target re-attained in mean ~2.2 ss
- **Hypotensive challenge (–20 mmHg):** Target re-attained in mean ~1.8 ss

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Acknowledgements and Selected References

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High blood pressure, or hypertension, is responsible for the deaths of over 7.6 million people—accounting for 13% of all deaths globally.

In the Emergency Department (ED), hypertensive patients have an 8% chance of death whereas non-hypertensive patients have 3% chance. This higher mortality rate is most often associated with:

- **Manual Error:** *Clinicians administer incorrect drug or infusion rate, leading to unsafe BP fluctuations.*
- **Time Delay:** *Adjustments to infusion rates often occur too slowly, allowing harmful deviations in BP to persist.*
- **Volatility:** *Giving drugs in large, one-time doses can create sharp spikes and crashes in BP rather than smooth control.*

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Graphs

