

# Supplementary Information for *Coordinated position–posture regulation framework for intestinal targeted drug delivery using a rotating-field cylindrical microrobot*

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## ABSTRACT

This supplementary information provides formal definitions of the performance metrics used in the main text and includes four additional figures illustrating extended results from multi-site delivery experiments. These materials further substantiate the robustness and reproducibility of the proposed rotating-field control framework.

## Supplementary Note 1: Definitions of Tracking-Error Metrics

To quantitatively evaluate the trajectory- and velocity-tracking performance of the microrobot, two standard error metrics were employed: the root-mean-square error (RMSE) and the mean absolute error (MAE). These metrics were computed independently for each planar motion axis  $\alpha \in \{x, y\}$ .

### Instantaneous Tracking Deviation

At any time instant  $t$ , the deviation between the reference trajectory  $\alpha_r(t)$  and the measured position  $\alpha(t)$  is defined as

$$e_\alpha(t) = \alpha_r(t) - \alpha(t), \quad (S1)$$

which characterizes the instantaneous tracking error along the  $\alpha$ -axis.

### Root-Mean-Square Error (RMSE)

The RMSE provides a global measure of tracking precision and penalizes larger deviations more strongly. It is defined as

$$\text{RMSE}_\alpha = \sqrt{\frac{1}{T} \sum_{t=0}^T e_\alpha^2(t)}, \quad (S2)$$

where  $T$  denotes the total number of sampled time steps.

### Mean Absolute Error (MAE)

To quantify the average steady-state deviation after transient behaviors subside, the MAE is computed as

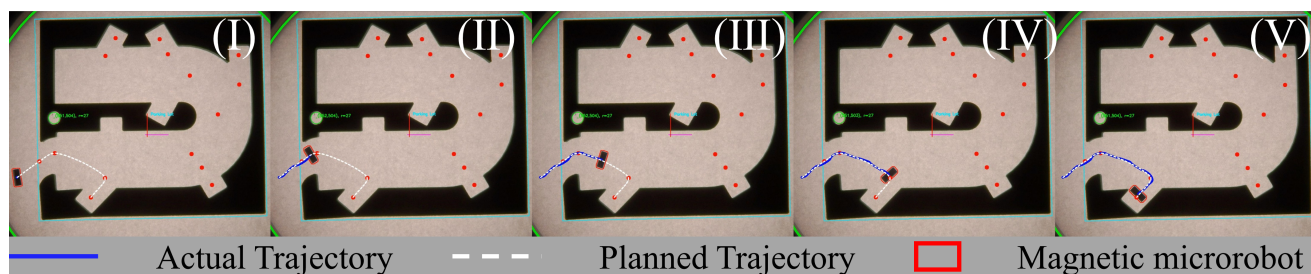
$$\text{MAE}_\alpha = \frac{1}{T} \sum_{t=0}^T |e_\alpha(t)|, \quad (S3)$$

which reflects the typical magnitude of tracking error during stable rolling motion.

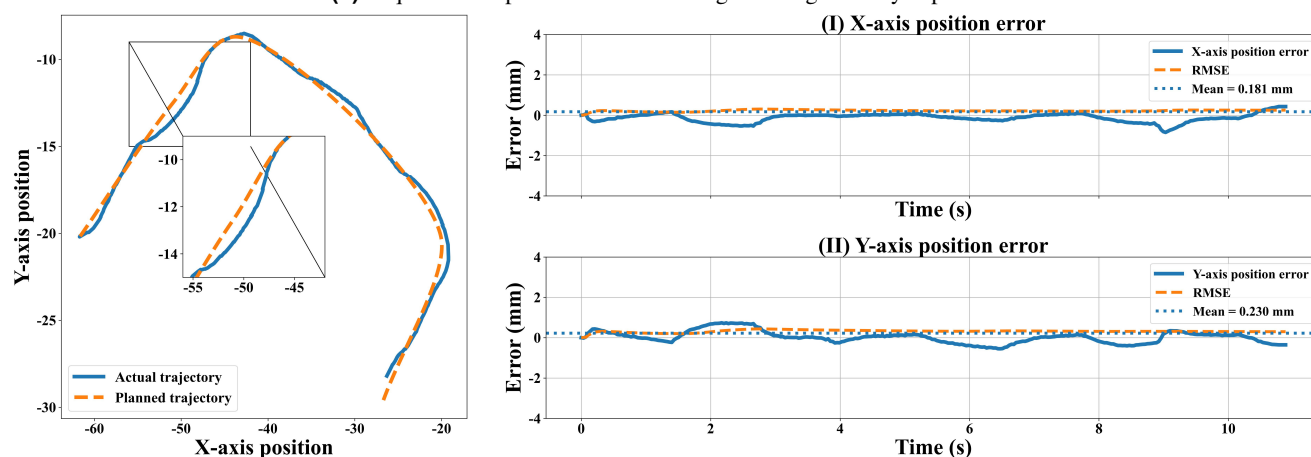
### Usage Across Experiments

These tracking-error metrics are used consistently throughout the main text in all trajectory-tracking, velocity-tracking, and full-process evaluations, including: Figure. 2(c): sinusoidal-path tracking experiments, Figure. 3(c)–(d): multi-site targeted delivery, Figure. 5(d)–(e): full-process delivery and retreat.

## Supplementary Figure

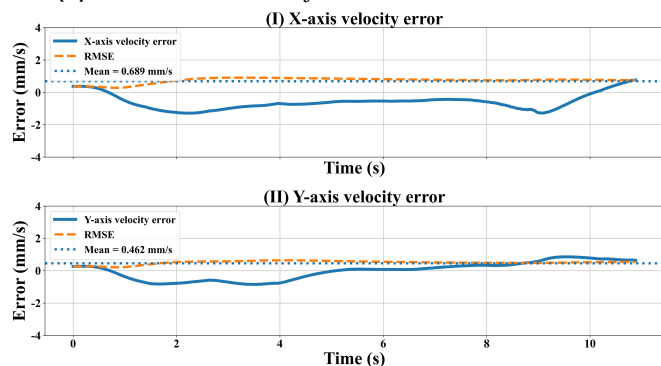


(a) Sequential snapshots of the T1P1 targeted drug-delivery experiment

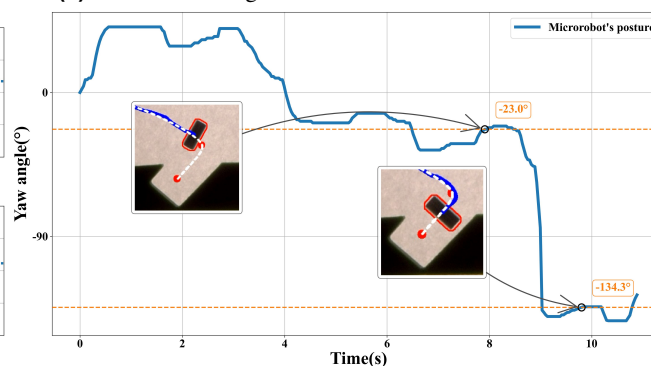


(b) Planned and actual trajectories

(c) Position-tracking errors and statistics

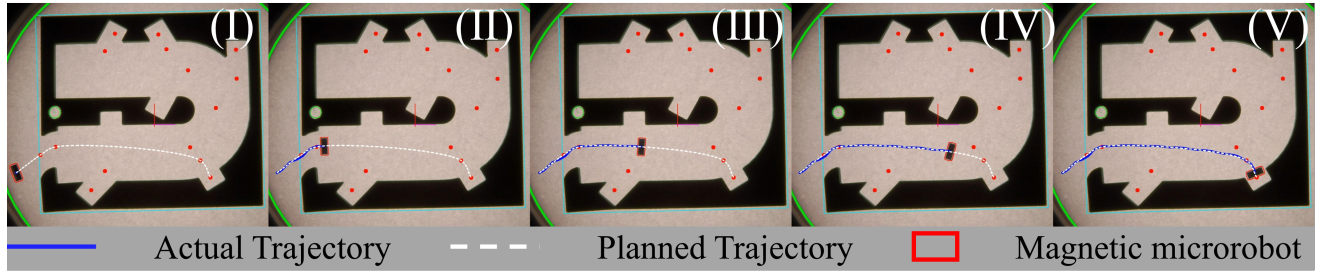


(d) Velocity-tracking errors and statistics

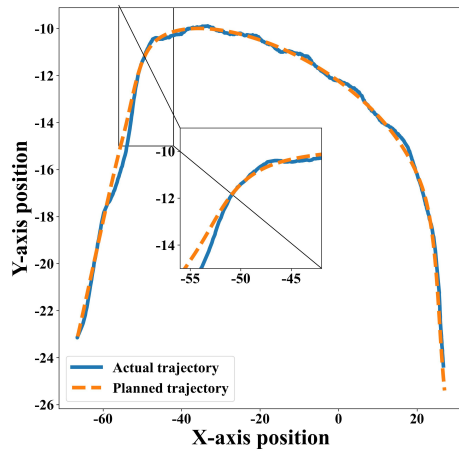


(e) Variation of the microrobot's yaw angle

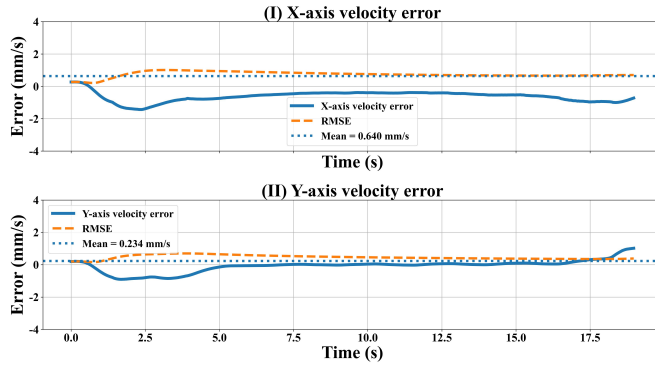
**Figure S1. T1P1 targeted drug-delivery performance under rotating-field actuation.** (a) Sequential snapshots showing the microrobot navigating to the predefined target site T1P1 and performing controlled drug release. (b) Comparison between the planned and actual trajectories, demonstrating stable motion and accurate path following. (c) Position-tracking results along the  $x$ - and  $y$ -axes, including instantaneous errors, root-mean-square errors (RMSEs), and mean absolute errors (MAEs). (d) Velocity-tracking performance along the  $x$ - and  $y$ -axes, with corresponding error curves and statistical metrics. (e) Variation of the microrobot's yaw angle during the T1P1 drug-delivery process, with two representative postures highlighted.



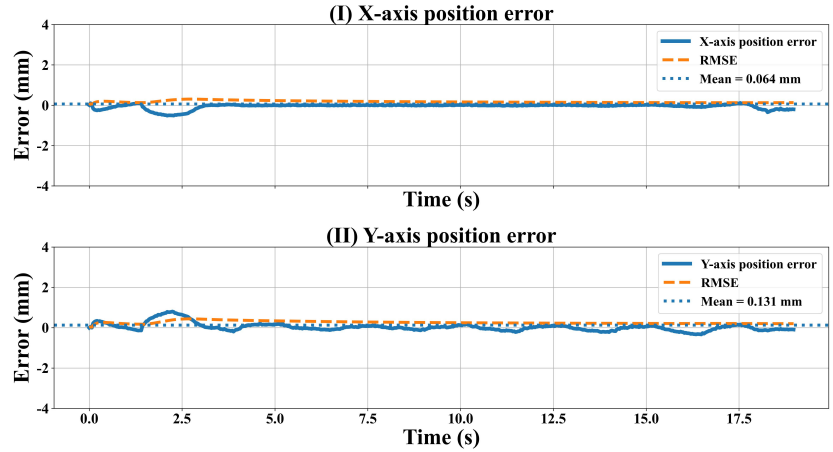
(a) Sequential snapshots of the T2P2 targeted drug-delivery experiment



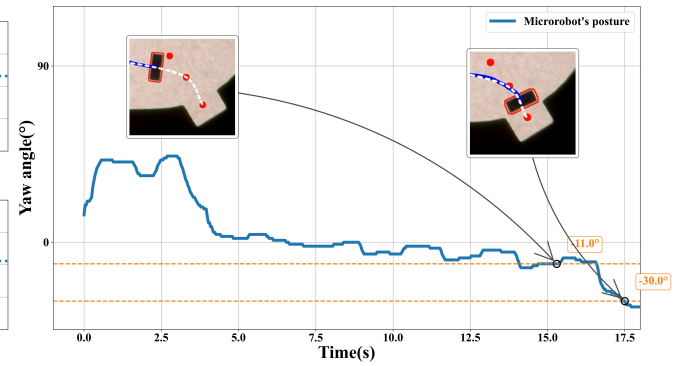
(b) Planned and actual trajectories



(d) Velocity-tracking errors and statistics

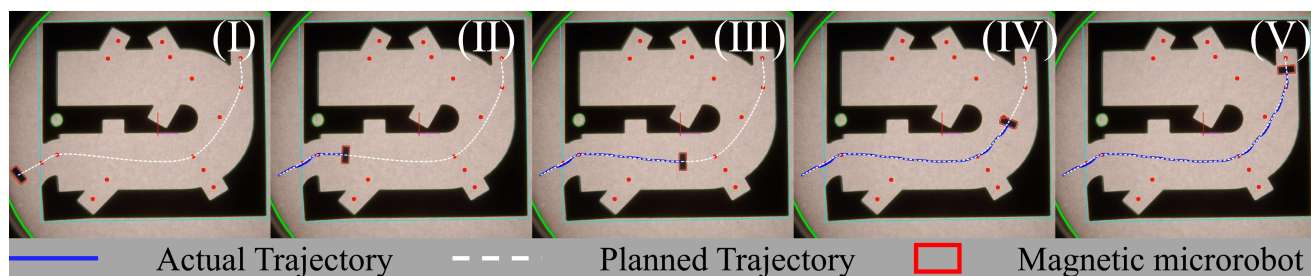


(c) Position-tracking errors and statistics

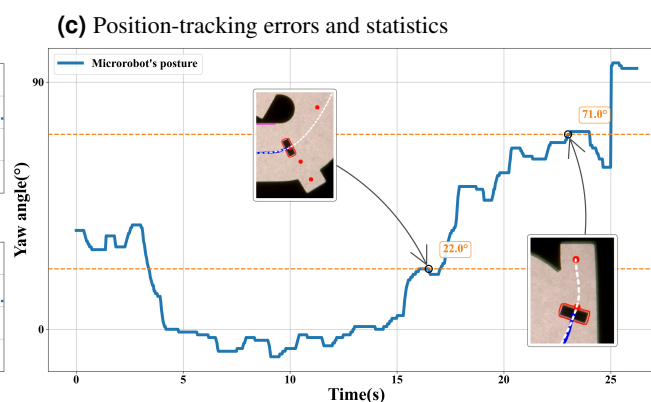
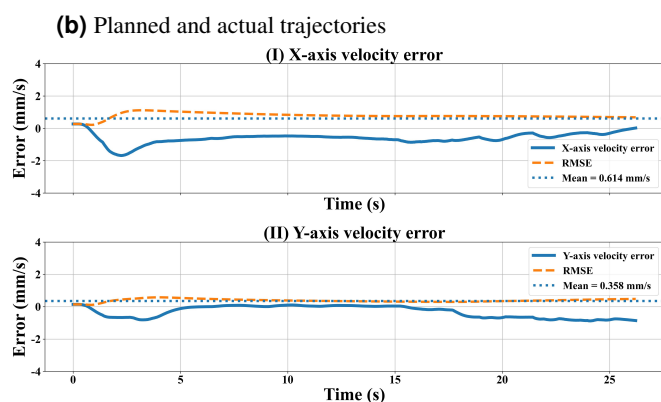
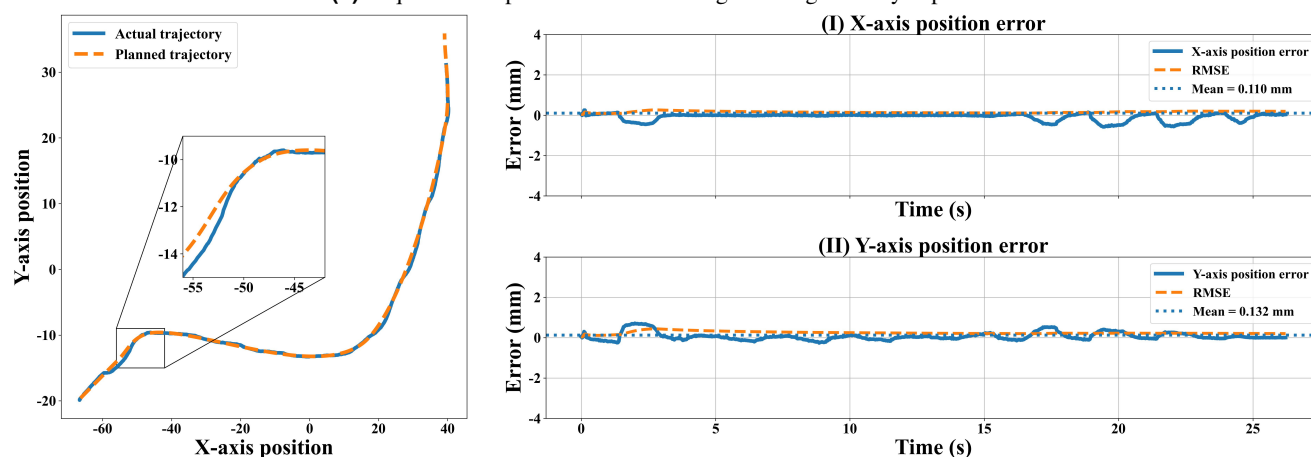


(e) Variation of the microrobot's yaw angle

**Figure S2. T2P2 targeted drug-delivery performance under rotating-field actuation.** (a) Sequential snapshots showing the microrobot navigating to the predefined target site T2P2 and performing controlled drug release. (b) Comparison between the planned and actual trajectories, demonstrating stable motion and accurate path following. (c) Position-tracking results along the  $x$ - and  $y$ -axes, including instantaneous errors, root-mean-square errors (RMSEs), and mean absolute errors (MAEs). (d) Velocity-tracking performance along the  $x$ - and  $y$ -axes, with corresponding error curves and statistical metrics. (e) Variation of the microrobot's yaw angle during the T2P2 drug-delivery process, with two representative postures highlighted.

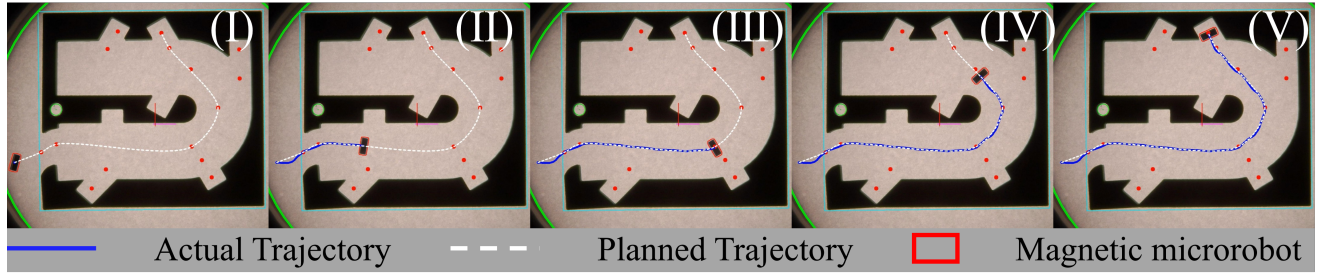


(a) Sequential snapshots of the T3P3 targeted drug-delivery experiment

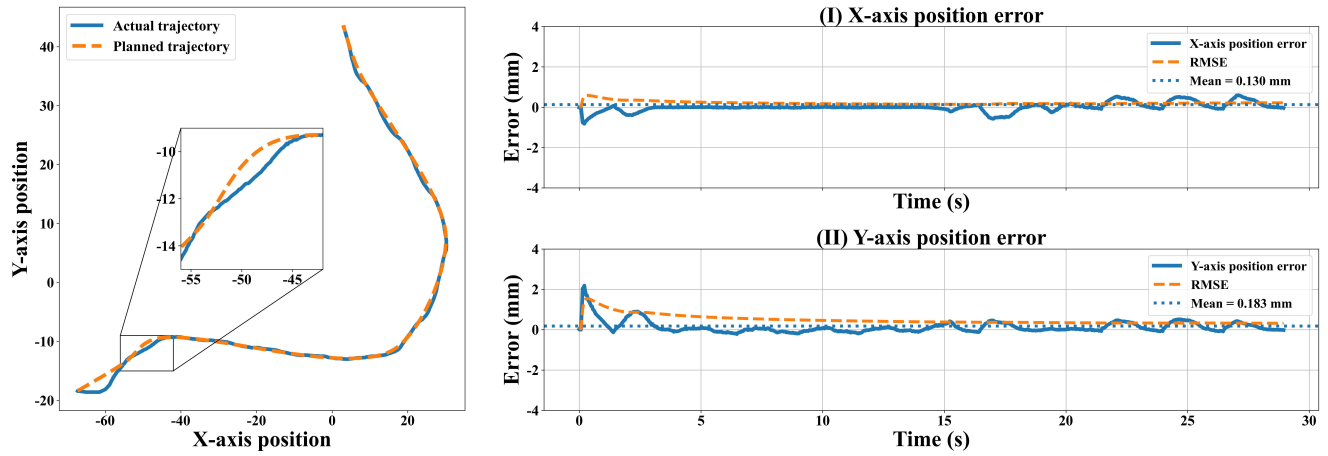


**Figure S3. T3P3 targeted drug-delivery performance under rotating-field actuation.** (a) Sequential snapshots showing the microrobot navigating to the predefined target site T3P3 and performing controlled drug release. (b) Comparison between the planned and actual trajectories, demonstrating stable motion and accurate path following. (c) Position-tracking results along the  $x$ - and  $y$ -axes, including instantaneous errors, root-mean-square errors (RMSEs), and mean absolute errors (MAEs). (d) Velocity-tracking performance along the  $x$ - and  $y$ -axes, with corresponding error curves and statistical metrics. (e) Variation of the microrobot's yaw angle during the T3P3 drug-delivery process, with two representative postures highlighted.



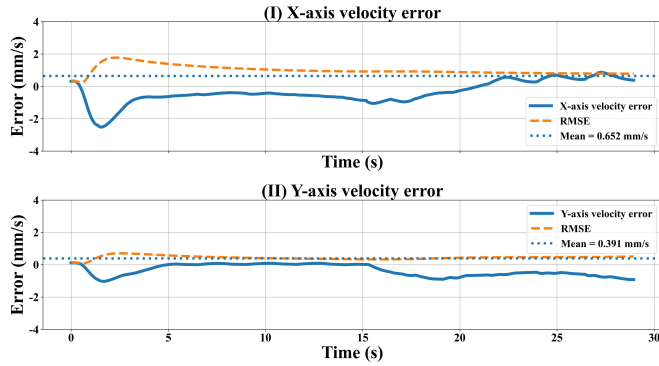


(a) Sequential snapshots of the T4P4 targeted drug-delivery experiment

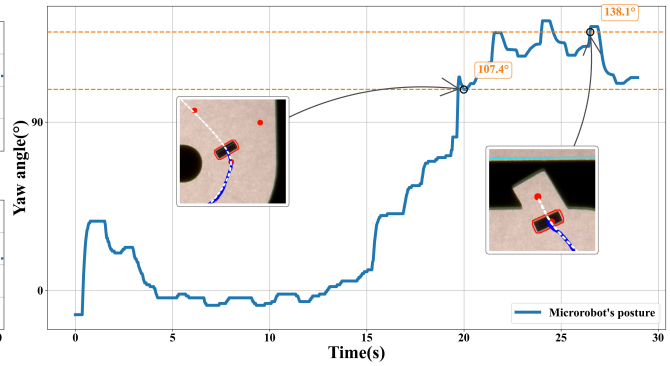


(b) Planned and actual trajectories

(c) Position-tracking errors and statistics



(d) Velocity-tracking errors and statistics



(e) Variation of the microrobot's yaw angle

**Figure S4. T4P4 targeted drug-delivery performance under rotating-field actuation.** (a) Sequential snapshots showing the microrobot navigating to the predefined target site T4P4 and performing controlled drug release. (b) Comparison between the planned and actual trajectories, demonstrating stable motion and accurate path following. (c) Position-tracking results along the  $x$ - and  $y$ -axes, including instantaneous errors, root-mean-square errors (RMSEs), and mean absolute errors (MAEs). (d) Velocity-tracking performance along the  $x$ - and  $y$ -axes, with corresponding error curves and statistical metrics. (e) Variation of the microrobot's yaw angle during the T4P4 drug-delivery process, with two representative postures highlighted.