A Unified Closed-Loop Motion Planning Approach for an I-AUV in Cluttered Environment with Localization Uncertainty

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I. Introduction

Background:

- ***I-AUV:*** a 6 Degree of Freedom (DOF) free-floating base with a n-DOF manipulator.
- ***Applications:*** conduct cleaning, data collection or inspection on underwater infrastructures or algae growing on the underside of sea ice in polar area.

Challenges:

- Non-uniform motion and observation noise (flow, landmark).
- Unified solution (planning, control, manipulator + base).
- Efficient optimal planning in high-dimensional belief space.

II. Problem Formulation

1. System model

$$\begin{aligned} \mathbf{x}_{t+1} &= f(\mathbf{x}_t, \mathbf{u}_t, \boldsymbol{\omega}_t) \\ \mathbf{z}_t &= h(\mathbf{x}_t, \boldsymbol{\nu}_t), \end{aligned} \xrightarrow{\text{Linearization}} \begin{aligned} \tilde{\mathbf{x}}_{t+1} &= \mathbf{A}_t^p \tilde{\mathbf{x}}_t + \mathbf{B}_t^p \tilde{\mathbf{u}}_t + \mathbf{G}_t^p \boldsymbol{\omega}_t \\ \tilde{\mathbf{z}}_t &= \mathbf{H}_t^p \tilde{\mathbf{x}}_t + \mathbf{M}_t^p \boldsymbol{\nu}_t \end{aligned}$$

$\mathbf{x}_t$ is manipulator and base state, G_t^p and M_t^p are weight matrices on motion and observation noise.

2. Problem definition

❖ ***Problem 1.*** **Find optimal control policy for stochastic optimal control.**

$$\min_{\pi} J^{\pi} := \mathbb{E}[\sum_{t=0}^{K-1} c_t^{\pi}(\mathbf{b}_t, \mathbf{u}_t) + c_K^{\pi}(\mathbf{b}_K)]$$

$$s.t.\ \mathbf{b}_{t+1} = \tau(\mathbf{b}_t, \mathbf{u}_t, \mathbf{z}_{t+1}),$$

$$g_i(\mathbf{b}_f, \mathbf{u}_t) \le 0, \quad i = 1, \dots m$$

Based on the separation principle of Linear Quadratic Gaussian, estimation cost is dominant. ***Problem 1*** is reduced to optimal trajectory planning with best estimation performance [1].

❖ ***Problem 2.*** **Unified I-AUV motion planning under uncertainty.**

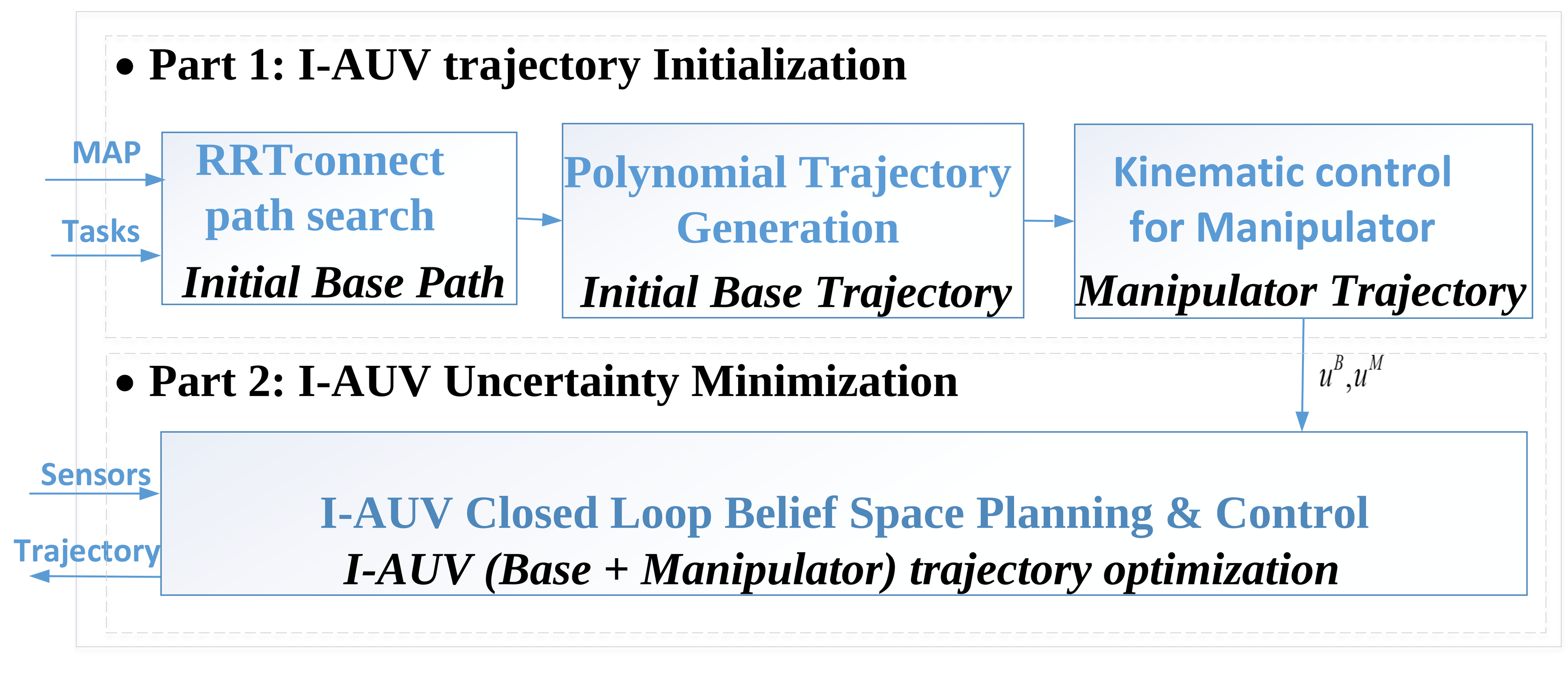
$$\min_{\mathbf{u}^p_{0:K-1}} \sum_{t=1}^{K} [-logDet(\mathbf{W}_t \Omega_t \mathbf{W}_t^T) + (\mathbf{u}^p_{t-1})^T \mathbf{W}_t^u \mathbf{u}^p_{t-1}]$$

$$s.t.\quad \bar{\Omega}_t = (A_t \Omega_{t-1}^{-1} A_t^T + G_t^p \Sigma_{\omega_t} (G_t)^T),$$

$$\Omega_t = H_t^T (M_t^p \Sigma_{\nu_t} (M_t^p)^T)^{-1} H_t + \bar{\Omega}_t, \text{ /*belief propagation*/}$$

$$g_i(\mathbf{u}_t) \le 0, \quad i = 1, \dots m \text{ , /*start, goal, control limit, etc.*/}$$

III. Solution framework



- u^B, u^M: initial base (B) and manipulator (M) trajectory.

[1]. Rafieisakhaei M, Chakravorty S, Kumar P R. T-LQG: Closed-loop belief space planning via trajectory-optimized LQG. *(ICRA 2017)*

IV. Solution

Part 1: I-AUV collision-free trajectory initialization

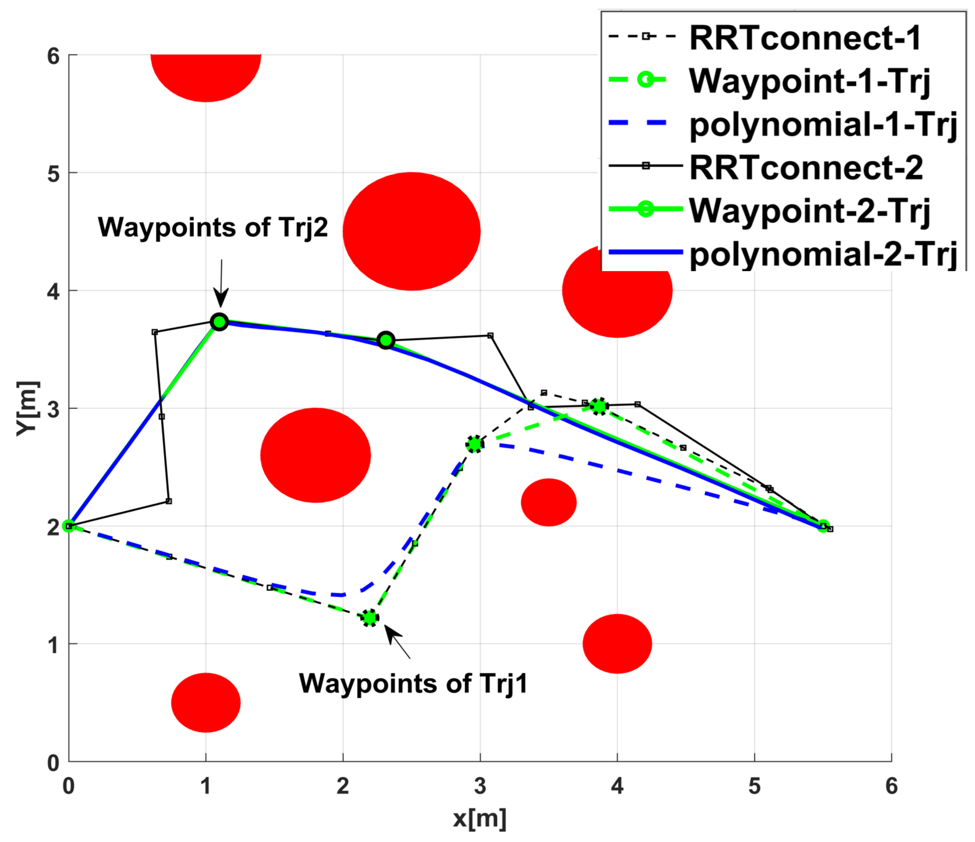
1). First step (base only): Waypoints search via RRT-connect.
2). Second step (base only): Polynomial trajectory optimization, linearly constrained by waypoints.

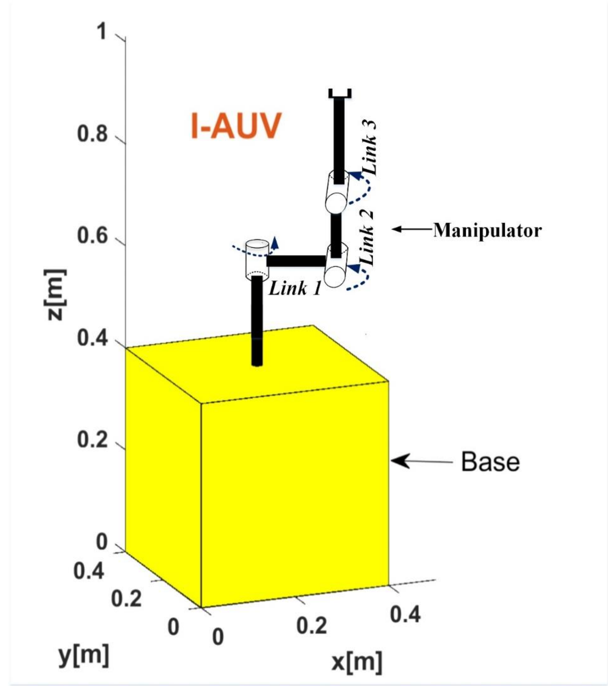
$$f^k(t) = a_0^k + a_1^k t + a_2^k t^2 + a_3^k t^3 + \dots + a_N^k t^N$$

$$J_p = \min_{\mathbf{d_P}} \ \omega_s J_s + \omega_c J_c + \omega_w J_w$$

3). Third step: Manipulator trajectory adaptation via Null-space control given the base motion, ***primary task***: base trajectory tracking, ***secondary task***: collision avoidance of manipulator.

$$\zeta_r = \boldsymbol{J}_a^{+}(\boldsymbol{\eta}, \boldsymbol{q}) \boxed{(\dot{\sigma}_{a,d} + \boldsymbol{k}_a \tilde{\sigma}_a)} + \mathbf{N}_a \boldsymbol{J}_b^{+}(\boldsymbol{\eta}, \boldsymbol{q}) \boxed{(\dot{\sigma}_{b,d} + \boldsymbol{k}_b \tilde{\sigma}_b)}$$



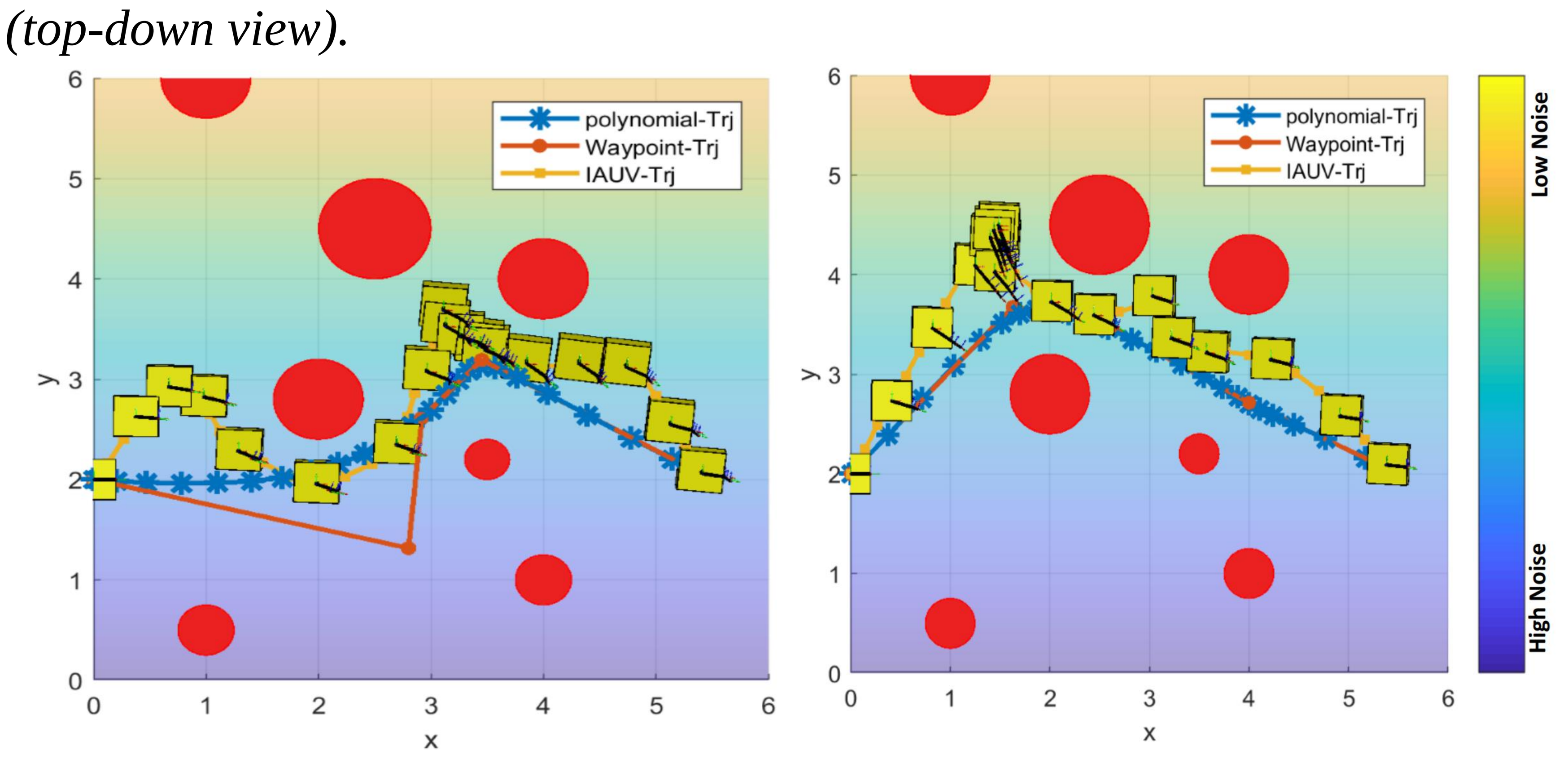


Part 2: I-AUV uncertainty minimization

1). Solve ***Problem 2*** via initials from part 1 and a SQP solver.
2). Compare the optimized trajectories and select an optimal one for LQR control.

V. Results

(a) *Case 1: Locally optimal solutions with a observation noise distribution (top-down view).*



(b) *Case 2: Optimal solution in cluttered scenario with same noise distribution.*