Robust Motion Planning Based on Sliding Horizon and Validated Simulation

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Introduction

Motion planning algorithms are a center piece in the control framework of mobile robots as they contribute to give them the ability of have autonomous behaviors. Furthermore, such class of algorithms is critical as a failure can cause the abort of the mission or can cause important amount of damage such as human loss. The validation of such algorithms is then mandatory in order to increase the confidence of the end users. However, those algorithms are also subject to constraints, *e.g.*, to reduce fuel consumption. So, computing a safe path is usually not enough, an optimal one is search to minimize some costs.

Moreover, one of the challenge in order to design robust and reliable motion planning algorithms is to take into account various sources of uncertainties. For example, the environment is not exactly known and some disturbance should have been considered. Mathematical models of the mobile robots are not perfect and usually come from some simplification in order to have efficient simulation activities. Lastly, computer-aided design usually produces approximated results as it is based on numerical methods which cannot produce close form solution of a problem, *e.g.*, the solution of an initial value problem for ordinary differential equations. The set-membership framework is suitable to deal with such kind of uncertainties.

Main contribution

The main contribution of this article is the combination of set-membership methods with optimizing approach. Hence, a correct-by-construction algorithm is defined with the intrinsic properties to be robust to uncertainties as it relies on set-membership approach [1]. Moreover, embedding the motion planning problem into a constraint satisfaction problem (CSP) [2], and more precisely into a global optimization framework [3], the proposed algorithm produces an optimal free-collision path with respect to a given cost function which is minimized.

Experimentation

The motion planning of an AUV which has to move the closest to the seabed is considered. Hence, the cost function is the depth of its gravity center. As safety constraints, we want to ensure that the AUV is closer to the seabed than the distance d_{max} and further than d_{min}.

Dynamics of an AUV

The dynamics of gravity center of the AUV follows the ODE defined in [4] and it is such that

$$\begin{cases} \dot{x} &= v\cos\theta\cos\psi \\ \dot{y} &= v\cos\theta\sin\psi \\ \dot{z} &= -v\sin\theta \\ \dot{\psi} &= \frac{\sin\varphi}{\cos\theta}\cdot v\cdot u_1 + \frac{\cos\varphi}{\cos\theta}\cdot v\cdot u_2 \\ \dot{\theta} &= \cos\varphi\cdot v\cdot u_1 - \sin\varphi\cdot v\cdot u_2 \\ \dot{\varphi} &= -0.1\sin\varphi + \theta\cdot v\cdot(\sin\varphi\cdot u_1 + \cos\varphi\cdot u_2) \end{cases} \tag{1}$$

with $\mathbf{s} = (x, y, z, \psi, \theta, \varphi)$ is the state vector. It can be split into the vector (x, y, z) of the coordinates of the gravity center and the vector (ψ, θ, φ) of Euler angles; $\mathbf{u} = (u_1, u_2)$ is the control input vector; v is the velocity.

Note that (1) has been simplified by substituting $\tan\theta$ by θ in the definition of $\dot{\varphi}$ to avoid technical issues of the implementation.

Nonetheless, the algorithm remains valid.

Underwater environment and results

We define a function $(x, y) \mapsto \text{seabed}\,(x, y)$ which returns the depth of the seabed at the coordinates (x, y). We also define d_{min} and d_{max} two constants such that the AUV stays at a distance to the seabed between d_{min} and d_{max}. Some constraints on AUV angles are considered: yaw and roll are bounded in an interval (to go in a quite straight way and to not capsize) and pitch is bounded by an extreme value (to limit the dive angle). Finally, in order to force the AUV to move forward through the x dimension, we impose $x_{\text{end}} > x_{\text{init}}$. Thus, the problem is to find the control $\mathbf{u}$ solution of

$$(P_{\text{AUV}}) : \begin{cases} \min_{\mathbf{u}} \quad z \\ \dot{\mathbf{s}} = \mathbf{f}(\mathbf{s}, \mathbf{u}) \\ z > \text{seabed}\,(x, y) + d_{\text{min}} \\ z < \text{seabed}\,(x, y) + d_{\text{max}} \\ x_{\text{end}} > x_{\text{init}} \\ \theta < 0.8 \\ \varphi, \psi \in [-0.5, 0.5] \end{cases}$$

Then the following seabeds are considered

- Seabed 1: $(x, y) \mapsto \text{seabed}\left(\frac{x-30}{20}, \frac{y}{2}\right) - 100$;
- Seabed 2: $(x, y) \mapsto \text{seabed}\left(\frac{y}{2}, \frac{x-30}{20}\right) - 100$;
- Seabed 3: $(x, y) \mapsto \text{seabed}\left(\frac{-x+30}{20}, \frac{y}{2}\right) - 100$;
- Seabed 4: $(x, y) \mapsto \text{seabed}\left(\frac{y}{2}, \frac{-x+30}{20}, \frac{y}{2}\right) - 100$.

Some results are given in Figure 1.

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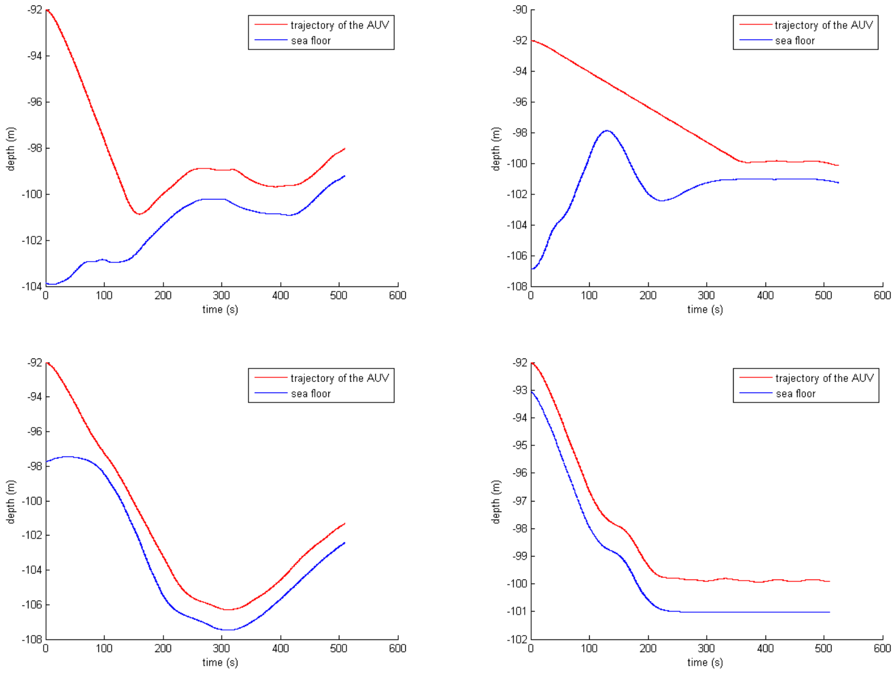

Figure 1: Results of the AUV motion planning with seabed 1 to 4 from top left to bottom right.

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