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Multi-UAVs tracking target in urban environment by model predictive control and Improved Grey Wolf Optimizer

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ABSTRACT

In this paper, based on the Model Predictive Control (MPC) and Improved Grey Wolf Optimizer (IGWO), a hybrid method is proposed to plan the optimal trajectories of multi-UAVs for target tracking in urban environment. Firstly, the target tracking problem in urban environment is modeled detailedly by formulating the visibility region, the sensor coverage area, the restricted region, the space constraints, etc. Based on the model of target tracking, the centralized MPC method is then adopted as the framework to obtain the trajectories of UAVs in real time, the objective of which is to optimize tracking performance under various constraints. In consideration of the computational complexity of this problem, IGWO, a novel intelligent algorithm with the advantages of good stability and strong search ability is utilized to solve the MPC formulation. It imitates the social hierarchy and predatory strategy of wolf pack, and some improvement strategies are also introduced e.g. the individual memory and the principle of survival of the fittest. Finally, the proposed method is demonstrated in a simulated urban environment. The simulation results show the effectiveness of the proposed hybrid method to solve target tracking problem.

1. Introduction

In the past few decades, unmanned aerial vehicle (UAV) has been increasingly utilized in civilian or military fields, e.g. search and rescue mission, reconnaissance, surveillance. Compared to manned vehicle, UAV has the advantages of strong adaptability, low cost and high safety. And more and more studies focus on enhancing the intelligence and autonomy level of UAVs [1,2].

Target tracking has been a research hotspot for several years, including the technology of target localization by image processing [3], multi-sensor information fusion [4], path planning [5], etc. And in this paper it is taken as a trajectory optimization problem, the main objective of which is to maintain the target being detected by UAV as long as possible. Compared to the case that single UAV performs task, the performance of team tracking by multi-UAVs will improve significantly, as UAVs can share information with each other and hence increase the sensor coverage i.e. field of view (FOV). There are mainly two modes for cooperative target tracking: centralized and decentralized approach. In centralized method, the center node will allocate the globally optimal missions to agents in the group; but in the decentralized approach, each agent will plan its corresponding path based on the information from other vehicles. In this paper, the centralized mode is utilized.

Various methods have been proposed and applied to path planning for cooperative target tracking. To solve the problem of standoff target tracking, Frew et al. [6] present the Lyapunov Guidance Vector Field (LGVF), where each UAV will converge to the expected limit cycle by heading-rate control and all the UAVs will distribute uniformly in phase by speed control. Chen et al. [7] propose the tangent guidance vector field (TGVF) to obtain the shortest route from the initial point to the limit cycle, but it only works well when UAV is outside of the limit cycle. To overcome the above disadvantage, LGVF and TGVF method are hence separately utilized when UAV is inside or outside of the limit cycle [8]. Dynamic programming approach is adopted to minimize the distance error covariance while the relative angle is ignored in Ref. [9]. The method based on the backstepping theory is presented by Lee et al. [10], to obtain the path which will globally approach to the target. Besides, there are other algorithms utilized in this area e.g. good Helmsman behavior, controlled collective motion, differential geometry, partially observable Markov decision processes (POMDP) [11–13].

However, most researches only focus on the target tracking problem in free or simple environment, which may be impractical for UAV application. In complex environment especially the urban environment studied in this paper, the collaborative track-

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ing task by multi-UAVs will be a more challenging and complicated optimization problem under various constraints. For example, the presence of dense buildings may occlude the line of sight (LOS) of UAV's sensor. On the other hand, UAV has a limited FOV, meaning that UAV cannot obtain the whole environment information. Besides, the restricted region, UAV dynamic constraints, and space constraints between UAVs should also be considered. Hence some effective methods are utilized to plan the optimal trajectories of UAVs. Shaferman et al. [14,15] model this problem detailedly and adopt the co-evolution genetic algorithm (CEGA) to optimize the tracking performance, but it is an off-line method assuming that the target motion is known. On this basis, Model Predictive Control (MPC) method is introduced in Ref. [16], but the optimal solution is only chosen from the uniformly distributed candidates.

MPC [17] has proven to be an effective method for process control industry, path planning, etc. Based on the future prediction and the optimization index, the future commands with limited time horizon are determined accurately. To solve MPC formulation, the mathematical optimization method e.g. dynamic programming can be utilized, but it has the drawback of combination blast when the dimension increases. Intelligent methods [18–20] have proven to be efficient to solve motion planning problem. Traditional intelligent methods consist of Particle Swarm Optimization (PSO), Differential Evolution (DE), Gravitational Search Algorithm (GSA), etc. Grey Wolf Optimizer (GWO), proposed by S. Mirjalili in 2014, is a new algorithm based on population search by imitating the social hierarchy and predatory strategy of wolfs [21]. GWO has the advantages of high convergence speed and good stability, and it has been developed and utilized in many fields [22–24]. In Ref. [23], differential evolution (DE) is integrated into GWO to force wolfs to jump out of the stagnation. This hybrid method proves to accelerate the convergence speed and improve the performance. Saremi et al. [24] utilize the evolutionary population dynamics (EPD) to remove the poor search agents of GWO and reinitialize the worst search agents around the search space. This method can significantly improve the performance including exploration, exploitation, local optimum avoidance, and convergence rate.

In this paper, a hybrid method is adopted to better solve the challenging problem of target tracking in urban environment. First, the target tracking problem is objectively modeled, especially considering the visibility region caused by LOS occlusion, the body-fixed sensor coverage area, the restricted region and other constraints. Second, the centralized MPC method is employed as the solving framework of target tracking problem, and the future UAV trajectories with finite horizon can be predicted and optimized in real time. Third, the improved Grey Wolf Optimizer (IGWO) is utilized as the solver of MPC, which is a GWO-based method with better performance by introducing some improvement strategies, e.g. the individual memory from PSO and the principle of survival of the fittest from DE. Overall, our proposed hybrid method has the following advantages. (1) The urban environment modeling is more credible and authentic, especially by considering LOS occlusion and body-fixed sensor coverage. (2) The adoption of MPC makes it possible to plan UAV paths in real time, which is crucial for target tracking in dynamic and unknown environment. (3) MPC formulation can be well resolved, as IGWO is superior to other methods in terms of convergence speed, convergence accuracy, and search ability.

The remaining paper is organized as follows. Section 2 models the target tracking problem in urban environment. Section 3 describes the MPC method. Then IGWO method is proposed for solving the formulation of MPC in Section 4. In Section 5, the hybrid method is verified by simulation. The conclusion is drawn in Section 6.

2. Mathematical formulation

The problem of multi-UAVs tracking target in urban environment is formulated mathematically in this section. The UAV model, target model, occlusions of line-of-sight, sensor coverage area, restricted regions and space constraints of UAVs are described respectively.

2.1. UAV model

We suppose that there are N_u homogeneous UAVs with the stable flight control system, where the commands of velocity, altitude or attitude can be well tracked. Each UAV is flying at the constant altitude h without considering the influence of wind. Then UAV model in the inertial frame can be expressed as:

$$\begin{cases} \dot{x}_i = v_i \cos\psi_i \\ \dot{y}_i = v_i \cos\psi_i \\ \dot{v}_i = a_i \\ \dot{\psi}_i = \dfrac{g \tan\phi_i}{v_i} \end{cases} \tag{1}$$

where $\boldsymbol{x}_i = [x_i, y_i]^{\mathrm{T}}$ is the horizontal position of ith UAV ($i = 1, \cdots, N_u$), v_i is the speed, ψ_i is the heading angle, g is the gravitational acceleration, ϕ_i is the roll angle and a_i is the speed acceleration. The control input of ith UAV consists of the roll angle and the speed acceleration i.e. $\boldsymbol{u}_i = [\phi_i, a_i]^{\mathrm{T}}$. Hence the control input of all the UAVs are $\boldsymbol{u} = [\boldsymbol{u}_1, \cdots, \boldsymbol{u}_{N_u}]^{\mathrm{T}}$ and the state vector of all the UAVs are $\bar{\boldsymbol{x}} = [\bar{\boldsymbol{x}}_1, \cdots, \bar{\boldsymbol{x}}_{N_u}]^{\mathrm{T}}$, where $\bar{\boldsymbol{x}}_i = [x_i, y_i, v_i, \psi_i]^{\mathrm{T}}$ is the state vector of ith UAV. Considering UAV performance, the following UAV dynamic constraints should be satisfied:

$$\begin{cases} v_{\min} \le v_i \le v_{\max} \\ |a_i| \le a_{\max} \\ |\phi_i| \le \phi_{\max} \end{cases} \tag{2}$$

where $v_{\min}$ and $v_{\max}$ are the minimum and maximum speed respectively, and $a_{\max}$ is the maximum speed acceleration, and $\phi_{\max}$ is the maximum roll angle.

2.2. Target model

The target is assumed to move in the horizontal plane with the state vector $\boldsymbol{x}_t = [x_t, y_t, \dot{x}_t, \dot{y}_t, \ddot{x}_t, \ddot{y}_t]^{\mathrm{T}}$. Hence the target model is given:

$$\boldsymbol{x}_t(k+1) = F\big(\boldsymbol{x}_t(k)\big) + \boldsymbol{w}(k) \tag{3}$$

where $F(\cdot)$ is the state-transition matrix, $\boldsymbol{w}(k)$ is the zero-mean Gaussian process noise i.e. $p(\boldsymbol{w}) \sim N(0, \boldsymbol{Q})$ and $\boldsymbol{Q}$ is the covariance matrix. The future motion of target can be obtained by fusion estimation and prediction e.g. unscented Kalman filter (UKF) or information filter (IF), which can be seen in Ref. [4].

2.3. Occlusions of line-of-sight

Compared to other environments, the main challenge in urban environment is that the presence of dense buildings may occlude the line of sight (LOS) of UAV's sensor. Therefore, the target tracking problem in urban environment will be very complicated and hard to solve.

Based on the target position and terrain information, the visibility region where the LOS exists is modeled in this paper. We define $\boldsymbol{X}^{hV}(\boldsymbol{x}_t)$ as the visibility region of target $\boldsymbol{x}_t$ at height h, which is shown as the grey area in Fig. 1. This region can be calculated by the Sweep Algorithm [14]. If UAV is in the visibility region i.e. the condition $\boldsymbol{x}_i \in \boldsymbol{X}^{hV}(\boldsymbol{x}_t)$ holds, the LOS of UAV will be unblocked and the target can hence be detected. By this method, the visibility