Generating Synthetic Training Data for Deep Learning-Based UAV Trajectory Prediction.

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Abstract: Deep learning-based models, such as recurrent neural networks (RNNs), have been applied to various sequence learning tasks with great success. Following this, these models are increasingly replacing classic approaches in object tracking applications for motion prediction. On the one hand, these models can capture complex object dynamics with less modeling required, but on the other hand, they depend on a large amount of training data for parameter tuning. Towards this end, we present an approach for generating synthetic trajectory data of unmanned-aerial-vehicles (UAVs) in image space. Since UAVs, or rather quadrotors are dynamical systems, they can not follow arbitrary trajectories. With the prerequisite that UAV trajectories fulfill a smoothness criterion corresponding to a minimal change of higher-order motion, methods for planning aggressive quadrotors flights can be utilized to generate optimal trajectories through a sequence of 3D waypoints. By projecting these maneuver trajectories, which are suitable for controlling quadrotors, to image space, a versatile trajectory data set is realized. To demonstrate the applicability of the synthetic trajectory data, we show that an RNN-based prediction model solely trained on the generated data can outperform classic reference models on a real-world UAV tracking dataset. The evaluation is done on the publicly available ANTI-UAV dataset.

1 INTRODUCTION

The rise of unmanned-aerial-vehicles (UAVs), such as quadrotors, in the consumer market has led to concerns about associated potential risks for security or privacy. The potential intended or unintended misuses pertain to various areas of public life, including locations, such as airports, mass events, or public demonstrations (Laurenzis et al., 2020). Thus, automated UAV detection and tracking have become increasingly important for security services for anticipating UAV behavior. Video-based solutions offer the benefit of covering large areas and are cost-effective to acquire (Sommer et al., 2017). The basic components of such a video-based approach are the appearance model and the prediction model which is traditionally realized with Bayesian filter. The prediction model tasks within detection and tracking pipelines, among others, are the prediction of the object behavior and bridging detection failures. Following the success of deep learning-based models in various sequence processing tasks, these models become the standard choice for object motion prediction. A significant drawback of deep learning models is the requirement of a large amount of training data. In order to overcome the problem of limited training data in the context of UAV tracking in image sequences, this paper proposes to utilize methods from planning aggressive UAV flights to generate suitable and versatile trajectories. The synthetically generated 3D trajectories are mapped into image space before they serve as training data for deep learning prediction models.

Despite the increasing number of trajectory datasets for object classes like pedestrians (e.g., TrajNet++
dataset (Kothari et al., 2020)) or vehicles (e.g., InD dataset (Bock et al., 2019)), datasets with UAV trajectories and UAV in general are very limited. For the aforementioned object classes of pedestrians and vehicles, mostly RNN-based deep learning models are successfully applied for trajectory prediction (Alahi et al., 2016). Independent of the existing deep learning variants for trajectory prediction relying on generative adversarial networks (GANs) (Amirian et al., 2019; Gupta et al., 2018), temporal convolution networks (TCNs) (Becker et al., 2018; Nikhil and Morris, 2018), and transformers (Giuliari et al., 2020; Saleh, 2020), an RNN-based prediction model is chosen as reference. The reader is referred to these surveys (Rasouli, 2020; Rudenko et al., 2020; Kothari et al., 2020) for a comprehensive overview of current deep learning-based approaches for trajectory prediction. Although the focus is on motion prediction and not on appearance modeling for UAV detection and tracking, we throw a brief glance at some of the current approaches that rely on images or use other modalities. Besides image-based methods, common modalities for UAV detections are RADAR, acoustics, radio-frequencies, and LIDAR. Comparisons of key characteristics of different deep learning-based approaches on single or fused modality information are presented in Samaras et al. (2019); Taha and Shoufan (2019); Unlu et al. (2019). A review with the focus on radar-based UAV detection methods is given by Christnacher et al. (2016). Approaches for acoustic sensors are, for example, presented in the work of Kartashov et al. (2020) and Jeon et al. (2017). An example to detect and identify UAVs based on their radio frequency signature is the approach of Xiao and Zhang (2019). For LIDAR, there exist, for example, the approaches of Hammer et al. (2019, 2018). Image-based approaches can be divided into using electro-optical sensors or infrared sensors. Their appearance modeling, however, is very similar. A further division can be made into one-stage strategies or two-stage strategies. In one-stage strategies, a direct classification and localization is applied. In two-stage strategies, a general (moving) object detection is followed by a classification step. For fixed cameras, the latter strategy is preferred. Different image-based approaches are, for example, presented in Schumann et al. (2018); Schumann et al. (2017), Sommer et al. (2017), Müller and Erdmüller (2019), and Rozanska et al. (2017).

The paper is structured as follows. Section 2 presents the proposed methods for generating realistic UAV trajectory data in image sequences. Section 3 briefly introduces the used RNN-based UAV trajectory prediction model. In addition to an analysis of the diversity of the synthetically generated data, section 4 includes an evaluation on the real-world ANTI-UAV dataset (Jiang et al., 2021). Finally, a conclusion is given in section 5.

2 SYNTHETIC DATA GENERATION

In this section the proposed approach for generating realistic, synthetic trajectory data is presented.

Minimum Snap Trajectories (MST): UAVs can not fly arbitrary trajectories due to the fact that they are dynamical systems with strict constraints on achievable velocities, accelerations and inputs. These constraints determine optimal trajectories with a series of waypoints in a set of positions and orientations in conjunction with control inputs (Mellinger, 2012). Thus, the goal of trajectory generation in controlling UAVs is to generate inputs to the motion control system, which ensures that the planned trajectory can be executed. Here, we apply an explicit optimization method that enables autonomous, aggressive, high-speed quadrotor flight through complex environments. In the remainder of this paper, the terms quadrotor and UAV are used interchangeably, although there exist various other UAV concepts. The principle procedure can be adapted to all other designs. Since we are only interested in the trajectory data, the actual control design can, to some extent, be neglected as long as the planned target trajectory is suitable for control.

Minimum snap trajectories (MST) have proven very effective as quadrotor trajectories since the motor commands and attitude accelerations of the UAV are proportional to the snap, or the fourth derivative, of the path (Richter et al., 2016). Of course, the difference between the target trajectory and the executed trajectory depends on the actual controller and physical limitations (e.g., maximum speed) of a UAV. Firstly, physical constraints can be considered in planning. Secondly, in most cases, a well-designed controller can closely follow the target trajectory. For our purpose, the trajectory of the actual flight can, in a way, be seen as only a slight variation of the target trajectory. However, quadrotor dynamics relying on four control inputs \((i_1, \ldots, i_4)\) for nested feedback control (inner attitude control loop and outer position control loop, see for example Michael et al. (2010)) are differential flat (Mellinger and Kumar, 2011). In other words, the states and the inputs can be written as functions of four selected flat outputs and their derivatives. This facilitates the automated generation of trajectories since any smooth trajectory (with reasonably bounded derivatives) in the space of flat outputs can
be followed by the quadrotor. Following Mellinger et al., the flat outputs are given by $p = [\mathbf{r}^T, \psi^T]^T$, where $\mathbf{r} = [x, y, z]^T$ are the coordinates of the center of mass in the world coordinate system and $\psi$ is the yaw angle. The flat outputs at a given time $t$ are given by $p(t)$, which defines a smooth curve. A waypoint denotes a position in space along a yaw angle. Trajectory planning specifies navigating through waypoints at specified times by staying in a safe corridor. Trivial trajectories such as straight lines lead to discontinuities in higher-order motion. Thus, such trajectories are undesirable because they include infinite curvatures at waypoints, which require the quadrotor to stop at each waypoint. The differentiability of polynomial trajectories makes them a natural choice for use in a differentially flat representation of the quadrotor dynamics. Thus, for following a specific trajectory with controller for a UAV, the smooth trajectory $p_T(t)$ is defined as piecewise polynomial functions of order $n$ over $m$ time intervals:

$$p_T(t) = \begin{cases} \sum_{i=0}^{n} P_{Ti}(t^i) & t_0 \leq t \leq t_1 \\ \sum_{i=0}^{n} P_{Ti}(t^i) & t_1 \leq t \leq t_2 \\ \vdots & \\ \sum_{i=0}^{n} P_{Ti}(t^i) & t_{m-1} \leq t \leq t_m \end{cases}$$

The goal is to find trajectories that minimize functionals which can be written using these basis functions. These kinds of problems can be solved with tools from the calculus of variations and are standard problems in robotics (Craig, 1989). Hence, in order to find the smooth target trajectory $p_T(t)_{tar}$, the integral of the $k_r^{th}$ derivative of position squared and the $k_{\psi}^{th}$ derivative of yaw angle squared is minimized:

$$p_T(t)_{tar} = \arg \min_{p_T(t)} \int_{t_0}^{t_f} \left[ c_r \frac{d^{k_r} \mathbf{r}^T}{dt^{k_r}} \right]^2 + c_{\psi} \frac{d^{k_{\psi}} \psi^T}{dt^{k_{\psi}}} dt$$

(2)

Here, $c_r$ and $c_{\psi}$ are constants to make the integrand non-dimensional. Continuity of the $k_r$ derivatives of $\mathbf{r}_T$ and $k_{\psi}$ derivatives of $\psi_T$ is enforced as a criterion for smoothness. In other words, the continuity of the derivatives determines the boundary conditions at the waypoints. As mentioned above, some UAV control input depends on the fourth derivative of the positions and the second derivative of the yaw. Accordingly, $p_T(t)_{tar}$ is calculated by minimizing the integral of the square of the norm of the snap ($k_r = 4$), and for the yaw angle, $k_{\psi} = 2$ holds.

The above problem can be formulated as a quadratic problem QP (Bertsekas, 1999). Thereby, $p_{Ti} = [x_{Ti}, y_{Ti}, z_{Ti}, \psi_{Ti}]^T$ are written as a $4n \times 1$ vector $\bar{c}$ with decision variables $\{x_{Ti}, y_{Ti}, z_{Ti}, \psi_{Ti}\}$:

$$\min \bar{c}^T Q \bar{c} + \bar{f}^T \bar{c}$$

subject to $A \bar{c} \leq \bar{b}$. 

(3)

Here, the objective function incorporates the minimization of the functional while the constraints can be used to satisfy constraints on the flat outputs and their derivatives and thus constraints on the states and the inputs. The initial conditions, final condition, or intermediate condition on any derivative of the trajectory are specified as equality constraint in 3. For a
more detailed explanation on generating MSTs, how to incorporate corridor constraints, and how to calculate the angular velocities, angular accelerations, total thrust, and moments required over the entire trajectory for the controller, the reader is referred to the work of Mellinger and Kumar (2011). Richter et al. (2016) presented an extended version of MST generation, where the solution of the quadratic problem is numerically more stable.

**Training Data Generation:** With the described method, we can generate MSTs suitable to aggressive maneuver flights for UAV control in a 3D environment. In order to generate versatile trajectory data in image space, further steps are required. The overall generation pipeline is explained in the following. Firstly, a desired camera model with known intrinsic parameters is selected. The selection depends on the targeted sensor set-up of the detection and tracking system. In our case, we choose a pinhole camera model without distortion effects loosely orientated on the ANTI-UAV dataset (Jiang et al., 2021) with regard to an intermediate image resolution (in pixels) (1176 × 640) between the infrared (640 × 512) and electro-optical camera (1920 × 1080) resolutions of the ANTI-UAV dataset. In case all camera parameters are known, the corresponding distortion coefficient should be considered. In the experiments the focal length (in pixels) is set to 1240, the principle point coordinates (in pixels) are set to $p_x = 579$, $p_y = 212$. For setting up the external parameters, the camera is placed close to the ground plane uniformly sampled from $Uni(1m, 2m)$ to set the height above ground. The inclination angle is sampled from $Uni(10°, 20°)$. Given the fixed camera parameters, the viewing frustum is calculated for a chosen near distance to the camera center ($d_{near} = 10m$) and a far distance to the camera center ($d_{far} = 30m$). For generating a single MST, a set of waypoints inside the viewing frustum is sampled. The number of waypoints is randomly varied between 3 and 7. The travel time for each segment is approximated by using the Euclidean distance between two waypoints and a sampled constant speed for the UAV $Uni(1m/s, 8m/s)$. The resulting straight-line trajectory serves as an initial solution of the MST calculation. The frame rate of the camera is sampled from $Uni(10fps, 20fps)$ for every run. In our experiments, we assumed a completely free space in the viewing frustum. As mentioned, corridor constraints, which can be used for simulating an object to fly through, can be integrated with the method of Mellinger and Kumar (2011). For the synthetic training dataset, 1000 MSTs are generated. The main steps for the synthetic data generation pipeline of a single run are as follows:

- Selection of a desired camera model with known intrinsic parameters.
- Extrinsic parameters are sampled from the height and inclination angle distribution.
- Calculation of the corresponding viewing frustum with $d_{near}$ and $d_{far}$.
- Sampling of waypoints inside viewing frustum.
- Estimation of the initial solution with fixed, sampled UAV speed.
- MST trajectory generation using the method of Mellinger and Kumar (2011).
- Projection of the 3D center of mass positions of the MST to image space using the camera parameters at fixed time intervals (reciprocal of the drawn frame rate of a single run).

This procedure is repeated until the desired number of samples are generated. Note that sanity checks and abort criteria for the trajectory are applied at the end and during every run. For example, requirements on the minimum and maximum length of consecutive image points. In Figure 1, generated MSTs along sampled waypoints in a 3D-environment are visualized. The viewing frustum for a fixed inclination angle of 15° is shown as a dotted gray line. The actual flight trajectory of a UAV is realized with a proportional–derivative (PD) controller as is proposed by Michael et al. (2010). Although the controller design is relatively simple, the UAV can closely follow the target trajectory. Thus, directly using the planned MST seems to be a legitimate design choice.

![Figure 2: Visualization of generated UAV trajectories as observed from the camera.](image-url)
3 PREDICTION MODEL

For trajectory prediction, an RNN-based model is considered, which predicts a distribution over the next $N$ image positions and is conditioned on the previous observations $\mathbf{u}^0$. As mentioned above, RNN-based models are a common choice from the variants of deep learning-based models for trajectory prediction. For generating the distribution over the next positions, the model outputs the parameter of a mixture density network (MDN). Such RNN-MDNs are applied to capture the motion of different object types. Originated from a model introduced by Graves (2014), modified versions have been successfully utilized to predict pedestrian (Alahi et al., 2016), vehicle (Deo and Trivedi, 2018) or cyclist (Pool et al., 2021) motions. Although these modified versions also incorporate some contextual cues (e.g., interactions from other objects), single objects motion is encoded with such an RNN-MDN variant.

Given an input sequence $\mathcal{U}$ of consecutive observed image positions $\mathbf{u}^t = (u^t, v^t)$ at time step $t$ along a trajectory, the model generates a probability distribution over future positions $\{\mathbf{u}^{t+1}, \ldots, \mathbf{u}^{t+N}\}$. The model is realized as an RNN encoder. With an embedding of the inputs and using a single Gaussian component, the model can be defined as follows:

$$\begin{align*}
\mathbf{e}^t &= \text{EMB}(\mathbf{u}^t; \mathbf{Θ}_e), \\
\mathbf{h} &= \text{RNN}(\mathbf{h}^{-1}, \mathbf{e}^t; \mathbf{Θ}_{\text{RNN}}), \\
\{\mathbf{μ}^{t+n}, \mathbf{Σ}^{t+n}\}_{n=1}^{N} &= \text{MLP}(\mathbf{h}; \mathbf{Θ}_{\text{MLP}}) \quad (4)
\end{align*}$$

Here, RNN(·) is the recurrent network, $\mathbf{h}$ the hidden state of the RNN, MLP(·) the multilayer perceptron, and EMB(·) an embedding layer. $\mathbf{Θ}$ represents the weights and biases of the MLP, EMB, or respectively of the RNN. The model is trained by maximizing the likelihood of the data given the output Gaussian distribution. This results in the following loss function:

$$L(\mathcal{U}) = -\sum_{n=1}^{N} \log \mathcal{N}(\mathbf{u}^{t+n}|\mathbf{μ}^{t+n}, \mathbf{Σ}^{t+n}). \quad (5)$$

Implementation Details: The RNN-MDN is implemented using Tensorflow (Abadi et al., 2015) and is trained for 2000 epochs using an ADAM optimizer (Kingma and Ba, 2015) with a decreasing learning rate, starting from 0.01 with a learning rate decay of 0.95 and a decay factor of $1/10$. The RNN hidden state and embedding dimension is 64. For the experiments, the long short-term memory (LSTM) (Hochreiter and Schmidhuber, 1997) RNN variant is utilized.

An example prediction of the RNN-MDN on a synthetically generated UAV trajectory in image space is depicted in Figure 3. On the left, the predicted distribution for 12 steps into the future is shown in blue. The corresponding ground truth position is marked as a green star. On the right, the corresponding 3D UAV trajectory is shown in green.

4 EVALUATION & ANALYSIS

This section analyzes the diversity of the generated synthetic data and the suitability for training deep-learning prediction models.
Figure 4: Data, aligned data and learned prototypes for the synthetic UAV trajectories projected to image space. The prototypes represent different motion patterns (from left to right): Constant velocity, curvilinear motion (left and right curve), acceleration and deceleration.

### Table 1: Results for a comparison between the an RNN-MDN prediction model trained on the synthetic generated data, a Kalman filter with CV motion model, and using linear interpolation. The prediction is done for 8, 10, and 16 frames into the future.

| Approach               | EO (1920 × 1080) | IR (640 × 512) |
|------------------------|-------------------|----------------|
|                        | 8/8               | 8/10           | 8/12           |
|                        | 8/8               | 8/10           | 8/12           |
| RNN-MDN                | 60.304 35.202     | 82.780 46.124  | 121.453 55.489|
| Kalman filter (CV)     | 81.061 60.333     | 110.041 84.550 | 179.459 104.408|
| Linear interpolation   | 86.998 67.113     | 119.106 89.067 | 183.558 108.522|
|                        | 20.849 18.604     | 41.378 21.100  | 61.459 24.490  |
| Kalman filter (CV)     | 22.340 24.630     | 43.172 32.522  | 68.012 37.047  |
| Linear interpolation   | 24.235 26.517     | 45.434 35.837  | 69.665 37.714  |

Diversity Analysis: For analyzing the diversity of the synthetically generated data, we use the approach of Hug et al. (2021). The approach learns a representation of the provided trajectory data by first employing a spatial sequence alignment, which enables a subsequent learning vector quantization (LVQ) stage. Each trajectory dataset can be reduced to a small number of prototypical sub-sequences specifying distinct motion patterns, where each sample can be assumed to be a variation of these prototypes (Hug et al., 2020). Thus, the resulting quantized representation of the trajectory data, the prototypes, reflect basic motion patterns, such as constant or curvilinear motion, while variations occur primarily in position, orientation, curvature and scale. For further details on the dataset analysis methods, the reader is referred to the work of Hug et al. (2021). The resulting prototypes of the generated training data are depicted in Figure 4.

The learned prototypes show that the generated synthetic data includes several different motion patterns. Besides, the diversity of the learned prototypes is visible. The dataset consists of, for example, distinguishable motion patterns reflecting constant velocity motion, curvilinear motion, acceleration, and deceleration.

Suitability Analysis: In order to analyze the suitability of the generated trajectory data, the RNN-MDN is trained as an exemplary deep learning-based prediction model according to section 3. For evaluation, the real-world ANTI-UAV dataset (Jiang et al., 2021) is used. The dataset consists of 100 high-quality, full HD video sequences (both electro-optical (EO) and infrared (IR)), spanning multiple occurrences of multi-scale UAVs, annotated with bounding boxes. As inputs for the prediction models, the center positions of the provided annotations are used. As classical reference models, a Kalman filter with a constant velocity (CV) motion model and linear interpolation are utilized. For the Kalman filter, the observation noise is assumed to be a white Gaussian noise process \( \vec{w} \sim \mathcal{N}(0, (1.5 \text{ pixels})^2) \). Thereby, the uncertainty in the annotation is considered. The process noise is modeled as the acceleration increment during a sampling interval (white noise acceleration model \( \sigma^2_{\text{CV}} = 0.5 \text{ pixels/ frame}^2 \)). For dealing with the minor annotation uncertainty, a small white Gaussian noise is added to the generated trajectory positions corresponding to the assumed ob-
Figure 5: Example predictions for the Anti-UAV dataset Jiang et al. (2021). The top images show two samples from the IR sequences. The bottom images depict two samples from the EO sequences.

The performance is compared with the final displacement error (FDE) for three different time-horizons, in particular, 8 frames, 10 frames, and 12 frames into the future. The FDE is calculated as the average Euclidean distance between the predicted final positions and the ground truth positions.

The results for the EO and the IR video sequences are summarized in table 1. Although the RNN-MDN is solely trained on the synthetically generated UAV data, the model could outperform the traditional reference models on the EO and the IR sequences of the ANTI-UAV dataset. It should be noted that no camera motion compensation is applied. Thus, the results of all considered prediction models can be further improved. For longer prediction horizons, all errors are relatively high due to the maneuvering behavior of the UAVs. However, in case the prediction model is utilized to bridge detection failures for supporting the appearance model of the detection and tracking pipeline, the number of subsequent failures should be lower than the shown 12 frames time horizon. Since the RNN-MDN relying on synthetic data achieved better performance than the reference models, it is better suited to anticipate the short-term UAV behavior. In Figure 5, the predicted distributions of future positions are visualized for the EO sequences or respectively IR sequences. The ground truth future positions are highlighted as green stars. The covariance ellipses around the predicted position are shown in blue. The final predicted positions are marked as a blue cross.

5 CONCLUSION

This paper presents an approach for generating synthetic trajectory data of UAVs in image space. By utilizing methods for planning maneuvering UAV flights, minimum snap trajectories along a sequence of 3D waypoints are generated. By selecting the desired camera model with known camera parameters, the trajectories can be projected to the observer’s perspective. To demonstrate the applicability of the synthetic trajectory data, we show that an RNN-MDN prediction model solely trained on the synthetically generated data is able to outperform classic reference models on a real-world UAV tracking dataset.
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