Non-Probability Sampling Network for Stochastic Human Trajectory Prediction

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Abstract

Capturing multimodal natures is essential for stochastic pedestrian trajectory prediction, to infer a finite set of future trajectories. The inferred trajectories are based on observation paths and the latent vectors of potential decisions of pedestrians in the inference step. However, stochastic approaches provide varying results for the same data and parameter settings, due to the random sampling of the latent vector. In this paper, we analyze the problem by reconstructing and comparing probabilistic distributions from prediction samples and socially-acceptable paths, respectively. Through this analysis, we observe that the inferences of all stochastic models are biased toward the random sampling, and fail to generate a set of realistic paths from finite samples. The problem cannot be resolved unless an infinite number of samples is available, which is infeasible in practice. We introduce the Quasi-Monte Carlo (QMC) method, ensuring uniform coverage on the sampling space, as an alternative to the conventional random sampling. With the same finite number of samples, the QMC improves all the multimodal prediction results. We take an additional step ahead by incorporating a learnable sampling network into the existing networks for trajectory prediction. For this purpose, we propose the Non-Probability Sampling Network (NPSN), a very small network (∼5K parameters) that generates purposive sample sequences using the past paths of pedestrians and their social interactions. Extensive experiments confirm that NPSN can significantly improve both the prediction accuracy (up to 60%) and reliability of the public pedestrian trajectory prediction benchmark. Code is publicly available at https://github.com/inhwanbae/NPSN.

1. Introduction

The goal of predicting pedestrian trajectories is to infer socially-acceptable paths based on previous steps while considering the social norms of other moving agents. Many earlier works [15, 39, 44, 59] on human trajectory prediction are based on deterministic approaches which yield the most likely single path. One of the earliest works in [15] models a social force using attractive and repulsive forces between pedestrians. Since then, motion time-series and agent interactions have been applied to trajectory forecasting. With the development of recurrent neural networks (RNNs), pioneering works such as, Social-LSTM [1] and Social-Attention [56], have adopted a social pooling and attention mechanisms between spatial neighbors. These approaches have become baseline models in areas such as spatial relation aggregation [13, 17, 40, 48, 50, 53] and temporal future prediction [23, 35, 36, 52, 63, 64].

Recently, generative models, which infer the distribution of potential future trajectories, are likely to inspire a major paradigm shift away from the single best prediction methods [6, 10, 13, 17, 18, 22, 23, 26, 27, 30–32, 35, 40, 47–54, 61, 65]. The generative models represent all possible paths, such that pedestrians may go straight, turn left/right at an intersection or take a roundabout way to avoid obstacles. To efficiently establish this multi-modality, a stochastic process is introduced to the trajectory prediction [13], which models the inferred uncertainty of pedestrians’ movements in every time frame. Stochastic trajectory prediction models start by generating a random hypothesis. Due to the non-deterministic nature of random sampling, the quality of the hypotheses depends on the number of samples. Ideally, an infinite number of hypotheses would be able to characterize all possible movements of pedestrians, but this is infeasible. In prac-
As another methodology, a generative model is introduced to predict realistic future paths. Social-GAN [13] firstly uses a generative framework that recursively infers future trajectory. The benefit of GAN is that it generates various outputs according to latent vectors. As a result, inter-personal, socially acceptable and multimodal human behaviors are accounted for in the pedestrian trajectory prediction. Such a research stream encourages to define a variety loss which calculates for the best prediction among multiple samples for diverse sample generation. [6,10,17,22,47,52].

Similarly, there have been attempts to predict diverse future generations using CVAE frameworks. DESIRE [23] uses a latent variable to account for the ambiguity of future paths and learns a sampling model to produce multiple hypotheses of future trajectories from given observations. This approach provides a diverse set of plausible predictions without the variety loss, and shares inspiration to objectives in many CVAE-based models [18,32,35,48,61].

All of these methods include a random sampling process and are sensitive to bias, due to the fixed number of samples, as above mentioned. In addition, current state-of-the-art models with CVAE frameworks outperform Gaussian distribution-based methods [40,50]. In this study, we analyze these phenomena with respect to the bias of stochastic trajectory prediction, and show that the Gaussian distribution-based approaches achieve noticeable performance improvements by minimizing the bias, even better than the CVAE-based methods. Lastly, we mention a recent deterministic approach [64] that predicts multiple trajectories, which is beyond the scope of this paper.

2.2. Learning latent variables

Some works account for the transformation of latent spaces by using prior trajectory information. PECNet [35] for example uses a truncation trick in latent space to adjust the trade-off between the fidelity and the variety of samples. In their learning approach, both IDL [28] and Trajektron++ [48] predict the mean and standard deviation of a latent distribution in an inference step. Rather than directly predicting the distribution parameters, AgentFormer [62] uses a linear transform of Gaussian noise to produce the latent vector. These methodologies still run the risk of bias because of the random sampling of the latent vectors. In the present work, we aim to reduce the bias using a discrepancy loss of a set of sampled latent vectors. 

2.3. Graph-based approaches

Pioneering works have introduced the concepts of social-pooling [1,13,52] and social-attention mechanisms [27,56,63] to capture the social interactions among pedestrians in
3.1. Problem Definition

We formulate the pedestrian trajectory prediction task as a multi-agent future trajectory generation problem conditioned on their past trajectories. To be specific, during the observation time frames $1 \leq t \leq T_{obs}$, there are $L$ pedestrians in a scene. The observed trajectory sequence is represented as $X^t_t|_{obs} = \{X^t_l | l \in [1, \ldots, L] \}$ for $\forall t \in [1, \ldots, L]$, where $x^t_l$ is the spatial coordinate of each pedestrian $l$ at time frame $t$. With the given observed sequence, the goal of the trajectory prediction is to learn potential distributions to generate $N$ plausible future sequences $Y^t_{1:T_{pred}} = \{Y^t_{l,n} | t \in [1, \ldots, T_{pred}], n \in [1, \ldots, N] \}$ for all $L$ pedestrians.

3.2. Stochastic Trajectory Prediction is Biased.

The generated trajectory $Y^t_{1:T_{pred}}$ comes from a distribution of possible trajectories which are constructed by pedestrians' movements based on social forces (Fig. 3). $\mathcal{T}_{true}$ is an expectation value computed with a plausible trajectory distribution, and $\mathcal{T}_{gen}$ is calculated with $Y^t_{1:T_{pred}}$ of $N$ which are independent and identically distributed (IID) random samples, i.e. the term is random if one uses different samples to generate trajectories. The expectation $\mathcal{T}_{gen}$ is a Monte Carlo estimate of integral, i.e. relevant expectation. Suppose that the expectation we want to compute from the trajectory distribution is $I(\tau) = \int_{0,1} \tau(x) q(x) dx$ which is the expected value of $\tau(x)$ for random variable $x$ with a density $q$ on $s$-dimensional unit cube $[0,1]^s$. Then, the Monte Carlo estimator for the generated trajectory distribution with $N$ samples can be formulated as below:

$$\hat{I}(\tau) = \hat{I}_{N,s}(\tau) = \frac{1}{N} \sum_{i=1}^{N} \tau(x_i),$$

$$Pr(\lim_{n \to \infty} \hat{I}(\tau) = I(\tau)) = 1,$$

where $Pr(\cdot)$ denotes a probability.

By the Strong Law of large numbers [12], the MC estimate converges to $I(\tau)$ as the number of samples $N$ increases without bound. Now, we assume that $\tau(x)$ has a finite variance $K(\tau)$ and define the error $\alpha$ as below:

$$\alpha = \hat{I}_{N,s}(\tau) - I(\tau),$$

$$\mathbb{E}[\alpha] = 0, \quad \text{var}(\alpha) = \frac{K(\tau)}{N},$$

where $\mathbb{E}$ is an expectation and $K(\tau)$ is $\int (\tau(x) - I(\tau))^2 q(x) dx$. Note that the $K(\tau)$ is non-negative and depends on the function being integrated. The algorithmic goal is to specify the procedure that results in lower variance estimates of the integral.

Now consider a function of the generator $F$, which is sufficiently smooth, in a Monte Carlo integral $I(\tau)$. We apply the Taylor series expansion of $F(I(\tau) + \alpha)$ as follows:

$$F(\hat{I}_{N,s}(\tau)) = F(I(\tau) + \alpha) \approx F(I(\tau)) + \alpha F'(I(\tau)) + \frac{\alpha^2}{2} F''(I(\tau)) + O(\alpha^3).$$
Therefore, the expectation value of $F(\hat{I}_{N,s}(\tau))$ can be formulated as below:

$$E[F(\hat{I}_{N,s}(\tau))] = F(\bar{I}(\tau)) + \frac{M}{N} + O\left(\frac{1}{N^2}\right), \quad (6)$$

where $M = K(\tau)(F''(I(\tau))/2)$ and the $\frac{M}{N}$ is a bias. Since the term $T_{\text{gen}}$ is estimated with an MC integration, the estimate must have a bias of $\frac{M}{N} + O\left(\frac{1}{N^2}\right)$. Note that the bias in the generated trajectories vanishes for $N \to \infty$, however, it is infeasible to utilize all infinite possible paths in practice. Since $M$ depends on the generator, the generated trajectories are differently biased depending on the number of generated samples as well as the generators, which is validated in Sec. 5.2.

### 3.3. Quasi-Monte Carlo for Trajectory Prediction

The QMC method utilizes a low discrepancy sequence including the Halton sequence [14] and the Sobol sequence [19]. Inspired by [43], we select a Sobol sequence which not only shows consistently better performances than the Halton sequence, but also is up to 5 times faster than the MC method, even with lower error rates.

From the view of numerical analysis, an inequality in [42] proves that low-discrepancy sequences guarantees more advanced sampling in Eq. (2) with fewer integration errors as below:

$$|\alpha| \leq V(\tau) D_N^*, \quad (7)$$

where $V(\tau)$ is a total variation of function $\tau$ which is bounded variation, and $D_N^*$ is the discrepancy of a sequence for the number of samples $N$. The inequality shows that a deterministic low-discrepancy sequence can be much better than the random one, for a function with finite variation. In the mathematics community, it has been proven that the Sobol sequences have a rate of convergence close to $O(\log N)^s/N$; for a random sequence it is $O(\sqrt{\log(\log N)}/N)$ in [42,43]. For faster convergence, $s$ needs to be small and $N$ large (e.g., $N > 2^s$). As a result, the low discrepancy sequences have lower errors for the same number of points ($N = 20$) as shown in Tab. 1.

As an example, since $x_i$ are IID samples from a uniformly distributed unit box for MC estimates, the samples tend to be irregularly spaced. For QMC, as $x_i$ comes from a deterministic quasi-random sequence whose point samples are independent, they can be uniformly spaced. This guarantees a suitable distribution for pedestrian trajectory prediction by successively constructing finer uniform partitions. Fig. 4 displays a plot of a moderate number of pseudo-random points in 2-dimensional space. We observe regions of empty space where there are no points generated from the uniform distribution, which produce results skewed towards the specific destinations. However, the Sobol sequence yields evenly distributed points to enforce prediction results close to socially-acceptable paths.

Unfortunately, low-discrepancy sequences such as the Sobol sequence are deterministically generated and make the trajectory prediction intractable when representing an uncertainty of pedestrians’ movements with various social interactions. Adding randomness into the Sobol sequence by scrambling the sequence’s base digits [3] is a solution to this problem. The resultant sequence retains the advantage of QMC method, even with the same expected value. Accordingly, we utilize the scrambled Sobol sequence to generate pedestrian trajectories to account for the feasibility, the diversity, and the randomness of human behaviors.

### 4. Non-Probability Sampling Network

In this section, we propose NPSN, which extends the sampling technique for pedestrian trajectory prediction based on the observed trajectory. Unlike the previous methods, which sample $N$ paths in a stochastic manner, we construct a model that effectively chooses target samples using a non-probabilistic sampling technique illustrated in Fig. 2-(d).

#### 4.1. Non-Probability Sampling on Multimodal Trajectory Prediction

In contrast to stochastic sampling, purposive sampling, one of the most common non-probability sampling techniques [4], relies on the subjective judgment of an expert to select the most productive samples rather than random selection. This approach is advantageous when studying complicated phenomena in in-depth qualitative research [38].

Since most people walk to their destinations using the shortest path, a large portion of labeled attributes in public datasets [25,44] are straight paths. Generative attribute models learn the probabilistic distributions of social affinity features for the attribute of straight paths. However, due to the multimodal nature of human paths, the models must generate as many diverse and feasible paths as possible, using only a fixed number of samples. As a possible solution, we can purposively include a variety of samples on turning left/right and detouring around obstacles. In purposive
We utilize an attention mechanism for modeling the social works [17, 50]. The GAT allows NPSN to aggregate the features, which relies on the purposive sampling, which generates a path closest to its ground truth, i.e., a large portion of the trajectory moving along one direction of the walkway. For this reason, we introduce a novel discrepancy loss to keep the N sample points with low-discrepancy, as below:

\[
\mathcal{L}_{\text{disc}} = \frac{1}{LN} \sum_{l=1}^{L} \sum_{i=1}^{N} \sum_{j=1}^{N} - \log \min_{j \neq i} \| S_{l,i} - S_{l,j} \|. 
\]  

(9)

The objective of discrepancy loss is to maximize distances among the closest neighbors of N samples. If the distance is closer, the loss imposes a higher penalty to ensure their uniform coverage of the sampling space.

The final loss function is a linear combination of both the distance and the discrepancy loss \( \mathcal{L} = \mathcal{L}_{\text{dist}} + \lambda \mathcal{L}_{\text{disc}} \). We set \( \lambda = 1e-2 \) to balance the scale of both terms.

4.3. Implementation Details

Transmission of one distribution to another. While most human trajectory prediction models use a normal distribution, the Sobol sequence and our NPSN are designed to produce a uniform distribution. We bridge the gap by transforming between the uniform distribution and the normal distribution. There are some representative methods including Ziggurat method [37], Inverse Cumulative Distribution Function (ICDF), and Box-Muller Transform [5]. In this work, we utilize the Box-Muller transform which is differentiable and enables an efficient execution on a GPU with the lowest QMC error, as demonstrated in [16, 67]. The formula of the Box-muller transform is as follows:

\[
Z_{\text{odd}} = \sqrt{-2 \ln(U_{\text{even}})} \cos(2\pi U_{\text{odd}}), \\
Z_{\text{even}} = \sqrt{-2 \ln(U_{\text{even}})} \sin(2\pi U_{\text{odd}}),
\]  

(10)

where \( U \) is an independent sample set from a uniform distribution and \( Z \) is an independent random variable from a standard normal distribution.

Training Procedure. Our NPSN is embedded into the state-of-the-art pedestrian trajectory prediction models [6, 13, 17, 32, 35, 40, 48, 50] by simply replacing their random sampling part. The parameters of the models are initialized using the weights provided by the authors, except for two models [17, 35] which use weights reproduced from the authors’ source codes. Our NPSN has only 5,128 learnable parameters on \( s = 2 \) and \( N = 20 \). We train the prediction models with NPSN using an AdamW optimizer [34] with a batch size of 128 and a learning rate of \( 1e-3 \) for 128 epochs. We step down the learning rate with a gain of 0.5 at every 32 epochs. Training time takes about three hours on a machine with an NVIDIA 2080TI GPU.
5. Experiments

In this section, we conduct comprehensive experiments on public benchmark datasets to verify how the sampling strategy contributes to pedestrian trajectory prediction. We first briefly describe our experimental setup (Sec. 5.1), and then provide comparison results with various baselines and state-of-the-art models (Sec. 5.2). Moreover, we run an extensive ablation study to demonstrate the effect of each component of our method (Sec. 5.3).

5.1. Experimental Setup

Dataset. We evaluate the effectiveness of the QMC method and our NPSN on various benchmark datasets [25, 44, 45, 60] over state-of-the-art methods. ETH [44] and UCB dataset [25] include ETH and HOTEL, and UNIV, ZARA1 and ZARA2 scenes, respectively. Both datasets consist of various movements of pedestrians with complicated social interactions. The Stanford Drone Dataset (SDD) [45] contains secluded scenes with various object types (e.g. pedestrian, biker, skater, and cart), and the Grand Central Station (GCS) [60] dataset consists of highly congested scenes where pedestrians walk. We observe a trajectory for 3.2 seconds ($T_{los} = 8$), and then predict future paths for the next 4.8 seconds ($T_{pred} = 12$). We follow a leave-one-out cross-validation evaluation strategy, which is the standard evaluation protocol used in many works [13, 17, 35, 40, 48, 50].

Evaluation metric. We measure the performance of the trajectory prediction models using three metrics: 1) Average Displacement Error (ADE) - average Euclidean distance between a prediction and ground-truth trajectory; 2) Final Displacement Error (FDE) - Euclidean distance between a prediction and ground-truth final destination; 3) Temporal Correlation Coefficient (TCC) [54] - Pearson correlation coefficient of motion patterns between a prediction and ground-truth trajectory. These metrics assess the best one of the evaluation metrics. In Fig. 5, we report the error variance for all agents in each scene. In addition, to reduce the variance in the prediction results of stochastic models, we repeat the evaluation 100 times and then average them for each metric.

Baseline. We evaluate QMC and NPSN sampling methods with representative stochastic pedestrian trajectory prediction models: 1) Gaussian distribution-based model - Social-STGNN [40], SGCN [50]; 2) GAN-based model - SocialGAN [13], STGAT [17], Trajectron++ [48], and PECNet [35] in N = 20. Models are evaluated on the ETH [44], UCB [25], SDD, and GCS datasets. (Gain: performance improvement w.r.t. FDE over the baseline models, Unit for ADE and FDE: meter. Bold: Best, Underline: Second best)

Table 1. Comparison results of MC, QMC and NPSN w.r.t. STGNN [40], SGCN [50], SocialSTGNN [40], UCY [25], SDD, and GCS datasets. (Gain: performance improvement w.r.t. FDE over the baseline models, Unit for ADE and FDE: meter. Bold: Best, Underline: Second best)
which acts as a linear transformation between the predicted trajectory coordinates and final coordinates. To be specific, the Gaussian-based models directly reflects the goodness of the QMC method, rather than deeper layers which may not be good enough over randomly generated samples. NPSN with $s=2$ is the sampling result from a low-discrepancy generator, i.e., smaller than other models ($s=5$). According to [24], for large dimensions $s$ and a small number of samples $N$, the sampling results from a low-discrepancy generator may not be good enough over randomly generated samples. The Gaussian-based model thus yields promising results compared to one which has larger sampling dimensions. 2) The performance improvements depend on the number of layers in networks (shallower is better): The CVAE and GAN-based models are composed of multiple layers. By contrast, the Gaussian-based models have only one layer which acts as a linear transformation between the predicted trajectory coordinates and final coordinates. To be specific, in the transformation, sampled independent 2D points are multiplied with the Cholesky decomposed covariance matrix and shifted by the mean matrix. Here, the shallow layer of the Gaussian-based models directly reflects the goodness of the QMC sampling method, rather than deeper layers which can barely be influenced by the random latent vector in the inference step.

**Evaluation of NPSN.** We apply NPSN to all three types of stochastic trajectory prediction models. As shown in Tab. 1, there are different performance gains according to the types. Particularly, the Gaussian distribution approaches (Social-GAN [40], SGCN [50]) show the highest performance improvement (up to 60%), which can be analyzed by the advantages of the QMC method when $s=2$. So far, the performance of the Gaussian distribution approaches has been underestimated due to the disadvantage of being easily affected by the sampling bias. Our NPSN maximizes the capability of the Gaussian distribution approaches through a purposive sampling technique.

In the CVAE based approaches, PECNet [35] shows a larger performance improvement (up to 41%) than that of Trajectron++ [48]. Since PECNet directly predicts a set of destinations through the latent vector, NPSN is compatible with its inference step. On the other hand, NPSN seems to produce less benefit with the inference step of Trajectron++ because it predicts the next step recurrently and its sample dimension is relatively large ($s=25$).

The generative models with variety loss, Social-GAN and STGAT, show relatively small performance improvements, compared to the others. For some datasets, the FDE values of STGAT are lower than those of MC and QMC when using our NPSN. This seems to suggest that NPSN fails to learn samples close to ground-truth trajectories due to the common entanglement problem of latent space [7, 20].

**Qualitative results.** Fig. 6 shows several cases where there are differences between the predictions of NPSN and other methods. Since NPSN takes an observation trajectory along with the low-discrepancy characteristics of the QMC method, the predicted paths from NPSN are closer to socially-acceptable paths compared to other methods.

As we described in the Fig. 4, the QMC method generates a more realistic trajectory distribution than the MC method. However, due to the limitations of the dataset, the generated trajectories of the baseline network are biased toward a straight path. On the other hand, NPSN sampling method alleviates the problem by selecting the point near the ground-truth in the latent space. As a result, the human trajectory model with NPSN not only generates well-distributed samples with finite sampling pathways, but also represents the feasible range of human’s movements.

|               | ETH | HOTEL | UNIV | ZARA1 | ZARA2 | A | VG |
|---------------|-----|-------|------|-------|-------|---|----|
| Social-GAN [13] | 0.87/1.62 | 0.67/1.37 | 0.76/1.52 | 0.35/0.68 | 0.42/0.84 | 0.61/1.21 |
| STGAT [17] | 0.65/1.12 | 0.35/0.66 | 0.52/1.10 | 0.34/0.69 | 0.29/0.40 | 0.43/0.83 |
| Social-STGNN [40] | 0.64/1.11 | 0.49/0.85 | 0.44/0.79 | 0.34/0.53 | 0.30/0.48 | 0.44/0.75 |
| PECNet [35] | 0.61/1.07 | 0.22/0.39 | 0.34/0.56 | 0.25/0.45 | 0.19/0.33 | 0.32/0.56 |
| Trajectron++ [48] | 0.43/0.86 | 0.12/0.19 | 0.22/0.43 | 0.17/0.32 | 0.12/0.25 | 0.21/0.41 |
| SGCN [50] | 0.57/1.00 | 0.31/0.53 | 0.37/0.67 | 0.29/0.51 | 0.22/0.42 | 0.35/0.63 |
| Causal-STGAT [6] | 0.60/0.98 | 0.30/0.54 | 0.52/1.10 | 0.32/0.64 | 0.28/0.58 | 0.40/0.77 |
| NCE-Trajectron++ [33] | 0.39/0.70 | 0.11/0.18 | 0.20/0.44 | 0.15/0.33 | 0.11/0.26 | 0.19/0.40 |
| NPSN-STGNN | 0.55/0.89 | 0.21/0.34 | 0.28/0.44 | 0.25/0.43 | 0.22/0.36 | 0.28/0.45 |
| NPSN-PECNet | 0.49/0.70 | 0.12/0.18 | 0.21/0.42 | 0.17/0.31 | 0.12/0.24 | 0.20/0.38 |
| NPSN-Trajectron++ | 0.72/1.26 | 0.38/0.72 | 0.71/1.43 | 0.34/0.68 | 0.33/0.70 | 0.50/0.96 |
| NPSN-SGCN | 0.61/1.02 | 0.31/0.57 | 0.53/1.13 | 0.34/0.68 | 0.30/0.62 | 0.42/0.80 |
| NPSN-SGAN | 0.44/0.62 | 0.21/0.34 | 0.28/0.44 | 0.25/0.43 | 0.22/0.36 | 0.28/0.45 |
| NPSN-STGAT | 0.55/0.85 | 0.19/0.29 | 0.29/0.44 | 0.21/0.33 | 0.16/0.25 | 0.28/0.44 |
| NPSN-Piecewise | 0.49/0.76 | 0.21/0.35 | 0.28/0.44 | 0.25/0.43 | 0.22/0.36 | 0.28/0.45 |
| NPSN-Trajectron++ | 0.56/0.90 | 0.25/0.40 | 0.51/1.09 | 0.32/0.65 | 0.27/0.56 | 0.38/0.72 |
| NPSN-Causal-STGAT | 0.36/0.69 | 0.11/0.18 | 0.18/0.31 | 0.14/0.29 | 0.11/0.23 | 0.18/0.35 |

Table 2: Comparison of NPSN with other state-of-the-art stochastic model (ADE/FDE, Unit: meter). The evaluation results are directly referred from [6, 33, 48]. Bold: Best, Underline: Second Best.
As mentioned above, it follows the Strong Law of large sample space dimension ($N<\infty$), discrepancy property: For small $N$ and a comparably large number in the MC integration. The Gaussian-based model, the QMC method may not be as as random sequence. We overcome these limitations with a learnable sampling method by sampling a feasible latent vector with low-discrepancy characteristics.

**Deterministic trajectory prediction.** Since the stochastic model is trained to predict multi-modal future paths, it outputs diverse paths at each execution, which is undesirable for deterministic human trajectory prediction, which infers only one feasible pathway ($N = 1$). By replacing the conventional probability process with a learnable sampling, NPSN allows the stochastic models to infer the most feasible trajectory in a deterministic manner. As shown in Fig. 7 (gray colored regions), NPSN outperforms QMC and the conventional methods on all the metrics at $N = 1$.

**Effectiveness of each component.** Lastly, we examine the effectiveness of each component in our NPSN, whose result is reported in Tab. 3. Here, SGCN [50] is selected as the baseline model because it shows the most significant performance improvements with NPSN. First, our two loss functions work well. Particularly, the discrepancy loss guarantees sample diversity by generating low-discrepancy samples, and the distance loss enforces generating samples close to the ground-truth trajectory. The GAT captures the agent-aware interaction for socially-acceptable trajectory prediction, except for the secluded ETH scene.

### 5.3. Ablation Studies

**Evaluation of different number of samples.** To check the effectiveness of the density of sampled paths in human trajectory prediction, we randomly generate trajectories by changing the number of samples $N$. As shown in Fig. 7, the performance gap between the MC and the QMC method is marginal when the number of samples goes to infinity. As mentioned above, it follows the Strong Law of large numbers in the MC integration. The Gaussian-based model, SGCN [50], achieves superior performance and improves more than 30% performance gain over the classic policy ($N = 20$). Since the sample dimension is small, the effectiveness and convergence of our NPSN are enlarged. Note that a performance drop over sparse conditions due to the discrepancy property: For small $N$ and a comparably large sample space dimension (i.e., $N < 2^s$), the discrepancy of

| ETH | HOTEL | UNIV | ZARA1 | ZARA2 | AVG |
|-----|-------|------|-------|-------|-----|
| Baseline | 0.57 / 1.00 | 0.31 / 0.53 | 0.37 / 0.67 | 0.29 / 0.51 | 0.22 / 0.42 | 0.35 / 0.63 |
| w/o $L_{\text{disc}}$ | 0.39 / 0.61 | 0.23 / 0.45 | 0.26 / 0.47 | 0.20 / 0.36 | 0.16 / 0.31 | 0.25 / 0.44 |
| w/o $L_{\text{dist}}$ | 0.38 / 0.66 | 0.16 / 0.25 | 0.23 / 0.39 | 0.18 / 0.32 | 0.24 / 0.25 | 0.22 / 0.32 |
| w/o GAT | 0.36 / 0.57 | 0.17 / 0.28 | 0.23 / 0.39 | 0.18 / 0.32 | 0.24 / 0.26 | 0.22 / 0.32 |
| sNPSN | 0.36 / 0.59 | 0.16 / 0.25 | 0.23 / 0.39 | 0.18 / 0.32 | 0.24 / 0.25 | 0.21 / 0.36 |

Table 3. Ablation study on each component of NPSN in SGCN.
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