

Progress-Aware Online Action Segmentation for Egocentric Procedural Task Videos

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Abstract

We address the problem of online (streaming) action segmentation for egocentric procedural task videos. While previous studies have mostly focused on offline action segmentation, where entire videos are available for both training and inference, the transition to online action segmentation is crucial for practical applications like AR/VR task assistants. Notably, applying an offline-trained model directly to online inference results in a significant performance drop due to the inconsistency between training and inference. We propose an online action segmentation framework by first modifying existing architectures to make them causal. Second, we develop a novel action progress prediction module to dynamically estimate the progress of ongoing actions and using them to refine the predictions of causal action segmentation. Third, we propose to learn task graphs from training videos and leverage them to obtain smooth and procedure-consistent segmentations. With the combination of progress and task graph with casual action segmentation, our framework effectively addresses prediction uncertainty and over-segmentation in online action segmentation and achieves significant improvement on three egocentric datasets.¹

1. Introduction

The future of computer vision holds exciting possibilities for seamlessly integrating augmented and virtual reality (AR/VR) into our daily lives. Imagine wearing AR glasses while you assemble or repair a complex machine, perform a medical procedure on a patient or cook a gourmet meal. Your **virtual task assistant** would recognize your actions in real-time, anticipate your next steps and guide you through the entire procedure. In this context, advanced computer vision technologies, including **online and real-time user action understanding**, become increasingly important.

¹Code is available at <https://github.com/Yuhan-Shen/ProTAS>.

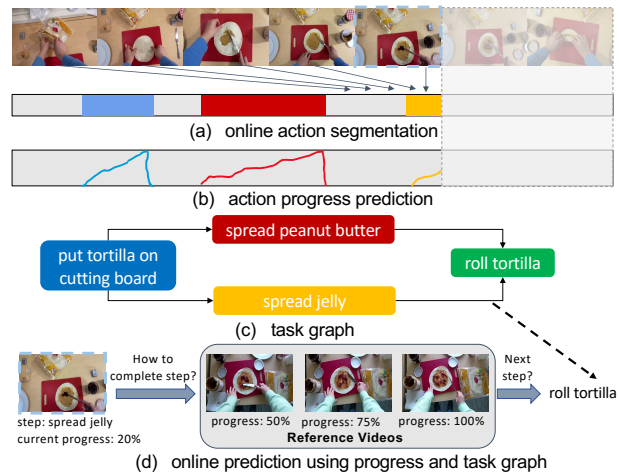


Figure 1. (a) Online action segmentation: use past and current frames to make predictions. (b) Action progress prediction: estimate the progress of each ongoing action in real time. (c) Task graph captures all feasible transcripts to perform a procedural task. We learn the task graph from training videos. (d) We use the predicted action progress and the learned task graph to improve online action predictions. Our framework allows us to demonstrate how to complete the current step based on the estimated progress and anticipate or guide the user to the next possible step(s).

While there have been extensive studies on video action segmentation, whose goal is to divide long videos (including procedural ones) into multiple segments of actions, the literature in this area has predominantly focused on *offline* action segmentation, where *entire* videos are given and used during both training and inference [2, 7, 22, 41, 45, 51, 52, 56, 64, 69–71, 73, 83–85, 87]. Such methods leverage past and future frames to predict the action of a given frame. However, achieving the vision of AR/VR task assistants requires a shift from traditional offline action segmentation to the dynamic realm of *online (streaming)* action segmentation, where actions must be recognized *as frames arrive*.

Notice that one can train an action segmentation model in an offline fashion and apply it online to all frames up to the current time or using a sliding window [28]. However, this approach suffers from major issues: i) it incurs a very

large computational cost, since we need to run the entire model every time new frames arrive; ii) the discrepancy between the offline training and online inference leads to low performance (as we show in our experiments), iii) the model often exhibits oversegmentation and abrupt transitions between actions, partly due to the lack of future frames. A few recent works have tried to address weakly-supervised online action segmentation [27, 28], but their performance is limited due to using weak supervision and their setting is different from what we study in this paper, which is *fully-supervised online* action segmentation.

Paper Contributions. We address the problem of online action segmentation, specially in the domain of egocentric procedural task videos captured through wearable AR/VR devices, see Figure 1. These videos offer a first-person view of human interaction with the environment as people handle objects and perform tasks. To address the challenges in online action segmentation, we propose a **PR**ogress-aware **O**nline **T**emporal **A**ction **S**egmentation (ProTAS) framework by introducing a novel component called Action Progress Prediction (APP). As shown in Figure 1(b), APP estimates the progress of each action as it proceeds, providing a dynamic and accurate assessment of the current state of ongoing actions. By equipping the model with the ability to estimate the progress of actions in real-time, it can make more informed and contextually relevant predictions during online action segmentation. This not only mitigates the problem of oversegmentation, but also ensures smoother transitions between actions, empowering the model to segment actions more accurately.

Moreover, we recognize that the inherent structure of procedural tasks can provide valuable cues for action segmentation. Therefore, we take a holistic approach by learning the task graph from training videos and incorporating it during both training and testing. Task graphs encode the temporal relationships and dependencies between actions (steps) within a task, offering a rich source of contextual information that enhances the precision and efficiency of online action segmentation by considering the completion status of the predecessors and successors of an action node in the graph. With the combination of the action progress prediction module and the task graph-based predictions, our model is able to segment streaming videos in an online fashion, achieving remarkable improvements on three egocentric procedural video datasets.

To address the lack of a sufficiently large egocentric procedural dataset from the cooking domain, we gathered 207 videos from 5 recipes, for a total of 16.6 hours of footage. We manually built the task graphs, captured videos corresponding to different variations of each task according to the task graph and carefully annotated the videos with frame-wise step labels. We plan to publicly release our dataset.

2. Related Works

Action Segmentation. Depending on the level of supervision, action segmentation can be classified into three main categories: unsupervised [3, 19, 20, 25, 42, 43, 65, 68, 76, 81, 90], weakly-supervised [11, 15, 24, 48–50, 53, 57, 57, 58, 61–63, 67, 73], and fully-supervised [2, 7, 22, 35, 36, 41, 45, 51, 52, 54, 59, 64, 69–71, 73, 84, 85, 87] approaches. Recent work in [46] has also studied joint temporal action segmentation and error detection. Our work primarily aligns with the fully-supervised methods. However, it is worth noting that previous studies have predominantly focused on offline action segmentation, where both past and future frames are utilized to make predictions at the current frame. This approach, while effective, faces limitations when applied to streaming videos, where access to future frames for prediction is impossible. Consequently, there exists a critical need to develop a robust online action segmentation model for real-world applications and scenarios where access to future frames is constrained. While a recent work OODL [27] has attempted to bridge the discrepancy between online and offline action segmentation, it only uses transcripts as weak supervision, which limits the performance. In contrast, our work is focused on online action segmentation using full supervision, aiming at developing reliable models for AR task assistants.

Online Video Understanding. While online action segmentation remains an understudied area, the online setting has been explored in other video understanding tasks. Online action recognition [8, 34, 44, 75] aims to recognize the action class of a video clip given a small fraction of frames. Online action detection [14, 21, 26, 79, 80, 82, 88] classifies per-frame action classes under the streaming video setting, where a video contains only one or very few actions. Online action localization [38, 39, 72] focuses on instance-level detection of actions in streaming videos. However, compared with these tasks, online action segmentation presents a notably greater challenge as segmenting actions requires a holistic long-range understanding of the videos. The temporal dependencies between actions are critical for accurate segmentation, and in the online setting, they become particularly challenging, due to the lack of future frames. Action anticipation [29, 30, 86] aims to predict the next step given the current video frames. While we both operate without access to future frames, our work produces precise frame-wise predictions of ongoing actions while action anticipation only predicts the class of the incoming action.

Action Progress Prediction. Our work draws inspiration from previous efforts on phase progression [16, 18, 31, 32, 55], which aim to estimate the progress of ongoing actions. Those works mainly concentrate on short video clips of individual actions, often ignoring relationships across multiple actions in the same video. In our work, we introduce

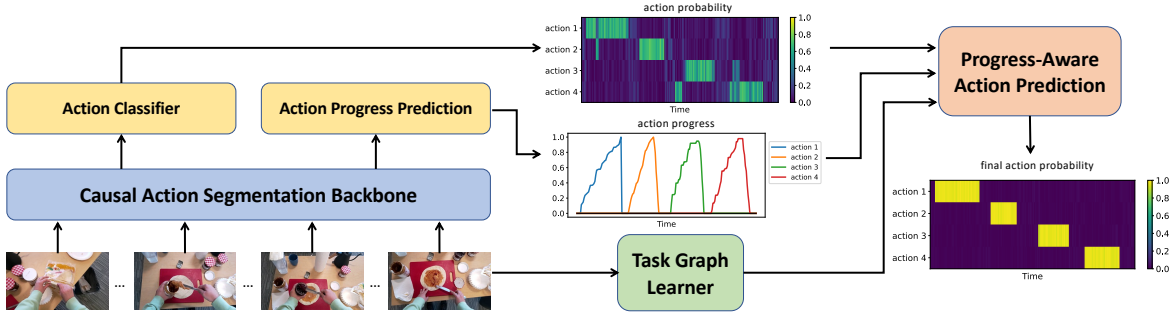


Figure 2. Illustration of our proposed progress-aware online temporal action segmentation (ProTAS) framework.

a progress monitoring module to keep track of various actions in the same video, and combine this information with procedural graphs to enhance online action segmentation.

Task Graph. Recent research on procedural videos has witnessed a growing interest in the integration of task graphs or knowledge graphs to leverage procedural knowledge to enhance performance [4, 17, 89]. This approach involves leveraging structured representations, often in the form of graphs, to encode information about the relationships and dependencies between different elements within a video. Task graphs are even more important in the online settings as the future information is unavailable. While Graph2Vid [17] has explored the use of flow graphs as a form of weak supervision for action segmentation, it is designed for offline action segmentation, as it requires dynamic programming between the entire video and the flow graph. In our paper, we propose to use the estimated progress to pinpoint the current state on the task graphs for online action segmentation, which has not been explored in the literature. [4] initially predicts keysteps in frames with high confidence and subsequently determines the maximum probability path for frames with low confidence using the task graph. However, it requires foreknowledge of the action labels of future frames, making it unsuitable for the online setting.

3. Problem Setting

We study the problem of *fully-supervised online action segmentation*. Assume we have a set of K actions and a test input video clip that consists of features of frames up to the current time t , denoted by $\mathcal{X}_t = (\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_t)$. Here, $t \in \{1, \dots, T\}$, where T is the length of the entire test video and $\mathbf{x}_t \in \mathbb{R}^D$ denotes the pre-extracted feature of frame t . The goal of an online action segmentation model, $g_{\text{online}}(\cdot)$, is to predict the K -dimensional vector $\mathbf{y}_t \in [0, 1]^K$ of the likelihood of actions at the current frame t , i.e.,

$$\mathbf{y}_t = g_{\text{online}}(\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_t). \quad (1)$$

For training, we have multiple full videos and their ground-truth action segmentation labels.

In contrast, offline action segmentation, $g_{\text{offline}}(\cdot)$, predicts the action of the frame t by using the entire video,

$$\mathbf{y}_t = g_{\text{offline}}(\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_t, \dots, \mathbf{x}_T). \quad (2)$$

Prior works on offline action segmentation have mainly employed Temporal Convolutional Network (TCN) [22, 45, 47, 52] or Transformers [7, 51, 85], which are non-causal, i.e., use also information from future frames to predict the current action. As we show in our experiments, models trained with future information (i.e., trained offline) have a significant performance degradation when tested online.

4. Proposed Online Temporal Action Segmentation Framework

Overview. We propose an online action segmentation framework with a focus on egocentric procedural videos, see Fig. 2. Our framework has the following components.

— First, we use a causal action segmentation (CAS) module by modifying existing architectures, where we use causal (dilated) convolutions for TCN-based models and causal masking for Transformer-based models, see Fig. 3. Therefore, prediction for each frame will be based on only the past and current information during training. This makes the training and testing similar and improves the online segmentation accuracy, as we show in the experiments.

— A main challenge in online action segmentation is oversegmentation (fluctuating action predictions), especially at the beginning, where not many frames are available. On the other hand, in egocentric videos, the scene contains cues about progress of an action. For example, the appearance of relevant objects may smoothly change as we progress, e.g., as we spread peanut butter on bread or fold paper filter, see Fig. 4. Therefore, we develop an action progress prediction (APP) module that estimates the progress made within an action and use it with the output of the CAS module to obtain more accurate and smoother action predictions. The progress can also be used as feedback in the AR/VR to notify the user of their progress and the amount of work remained in a step, see Fig. 1(d).

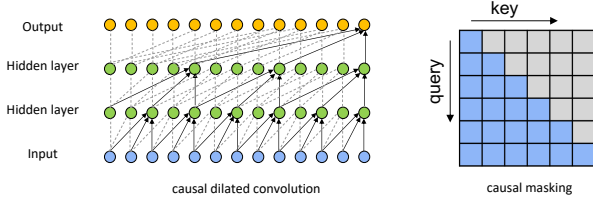


Figure 3. Left: In causal dilated convolution, the filter operates on past and present data without access to future data. Right: In causal masking, the attention mechanism only attends to previous elements in a sequence.

— Task graph encodes important information about plausible sequences of actions, see Fig. 1(c). In particular, the successors of an action cannot start unless the action is completed (full progress), while to start an action all its predecessors must be completed. Obtaining and leveraging such relationships allow us to find plausible and smooth predictions. Therefore, we propose a method to estimate the task graph from training videos (without using external knowledge sources as in [4, 89]) and to leverage it with action progress during both training and inference.

Next, we describe each component in more details.

4.1. Causal Action Segmentation (CAS)

To ensure consistency between the inference and training setting and subsequently improve the action segmentation performance, we first modify existing architectures to be causal, i.e., depend only on current and past frames, see Fig. 3. For TCN-based methods, we replace dilated convolutions with causal dilated convolutions [77]. Causal dilated convolutions are designed to only incorporate past and current frame information. For Transformer-based methods, we use causal masking [78], where the model can only attend to past frames within the self-attention mechanism, preventing it from accessing future information.

Similar to prior works on offline action segmentation [22, 83, 85], we use the frame-wise cross-entropy loss and smoothing loss for training,

$$\begin{aligned} \mathcal{L} &= \mathcal{L}_{\text{cls}} + \lambda_{\text{smo}} \mathcal{L}_{\text{smo}} \\ &= \frac{1}{T} \sum_t -\log(y_{t,q_t}) + \frac{\lambda_{\text{smo}}}{TK} \sum_t \sum_k (y_{t-1,k} - y_{t,k})^2, \end{aligned} \quad (3)$$

where q_t is the ground-truth label of the t -th frame, y_{t,q_t} is the predicted probability of the ground-truth label q_t at frame t and λ_{smo} is the weight for the smoothing loss.

4.2. Action Progress Prediction (APP)

In the online setting, the small number of frames especially at the beginning leads to fluctuating and unreliable predictions. The progress of an action, on the other hand, can inform the action prediction. For example, if the user has made about 30% progress in an action at the previous time instants, they will continue performing the same action at

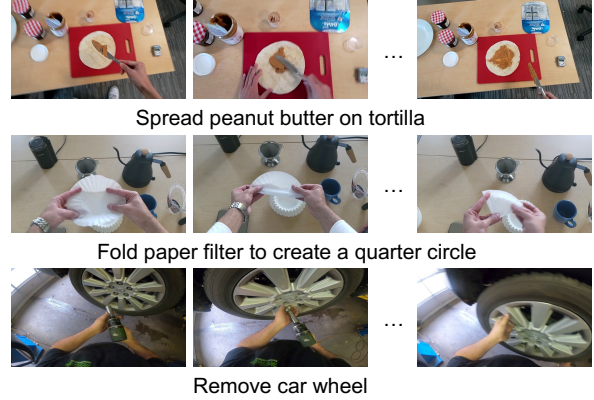


Figure 4. The scene contains progress cues. For example, the appearance of step-relevant objects may smoothly change as we progress in the step.

the current time with high probability. On the other hand, if an action has been completed (about 100% progress), a new action is likely to occur at the current time.

We propose an action progress prediction (APP) module to estimate the progress of each action as it unfolds. APP is a regression branch and works in parallel to the causal action segmentation branch. Specifically, we use a Gated Recurrent Unit (GRU) layer [12] to estimate the progress given its dynamically evolving characteristics. We predict the progress of each action separately. We concatenate the raw action probabilities from CAS and the progress estimations from APP, and feed them through a progress-driven prediction module, which consists of a Multi-Layer Perceptron (MLP), to output the final action segmentation probabilities, see Fig. 2. These final probabilities are indeed a refinement of the raw action probabilities conditioned on action progress estimation. Thus, our model is able to mitigate oversegmentation and abrupt transitions between actions, as we show in the experiments.

To learn the progress from training videos, given a segment $[t_s, t_e]$ belonging to action k , we define the target action progress at frame t as the fraction of the action duration that has already passed, i.e.,

$$p_{t,k}^* = \frac{t - t_s}{t_e - t_s} \in [0, 1], \quad (4)$$

where the target progress value at the starting frame is $p_{t_s,k}^* = 0$ and at the ending frame (completion moment) is $p_{t_e,k}^* = 1$. This target linear progress is similar to existing literature in phase progression and action completion [6, 16, 18, 31–33, 55]. We use Mean Squared Error (MSE) loss to supervise the progress learning, i.e.,

$$\mathcal{L}_{\text{prog}} = \frac{1}{TK} \sum_t \sum_k (p_{t,k} - p_{t,k}^*)^2, \quad (5)$$

where $p_{t,k}$ is the prediction from the APP module.

4.3. Leveraging Task Graph

Task graph captures partial orderings of actions and provides all feasible ways to execute a task, see Fig. 1(c). More specifically, an action node can only start when all its predecessors are completed. Thus, the task graph encodes i) prerequisites that must precede the execution of a specific action (e.g., we must take out the tortilla from its bag and put it on board before applying jam on it), ii) irreversible constraints that some actions cannot be performed after the completion of a particular action (e.g., we cannot apply peanut butter again after we have rolled the tortilla). We propose to learn (see next subsection) and leverage the task graph for plausible and smooth online action segmentation during both training and inference.

Let $\mathcal{A}^p(k)$ and $\mathcal{A}^s(k)$ denote, respectively, the set of predecessors and successors of the action node k in the task graph. We use the Breadth-First Search (BFS) algorithm [1, 17] to traverse the parent-child relationships of each action node k to obtain its predecessors and successors. We design a loss that enforces predicting an action k at time t must incur a penalty when i) its predecessors have not been completed, ii) some of its successors are (being) completed. Thus, we first need to have an estimate of the completion state of an action. We use progress predictions to compute the completion state of action k at time t as

$$c_{t,k} = \max_{t'=1,2,\dots,t-1} p_{t',k} \in [0, 1]. \quad (6)$$

Thus, when $c_{t,k}$ is close to 1, the action k was close to completion in the previous frames.

For each action k at time t , we define two scores. One score indicates how far the *predecessors* of k are from completion at time t ,

$$\alpha_{t,k}^p = \sum_{k' \in \mathcal{A}^p(k)} (1 - c_{t,k'}). \quad (7)$$

The score will be zero when all predecessors of k are completed before frame t , otherwise it will be positive. The second score indicates whether any *successor* of k has been in progress before time t ,

$$\alpha_{t,k}^s = \sum_{k' \in \mathcal{A}^s(k)} c_{t,k'}. \quad (8)$$

This score will be zero when no successor of k has started before time t , otherwise it will be positive.

To have predictions that satisfy the predecessors and successors requirements, we introduce a task-graph loss,

$$\mathcal{L}_{\text{graph}} = \frac{1}{TK} \sum_t \sum_k (\alpha_{t,k}^p + \alpha_{t,k}^s) \cdot y_{t,k}, \quad (9)$$

which enforces that when at time t action k is predicted ($y_{t,k} = 1$), then the predecessors of k must have been completed (i.e., $\alpha_{t,k}^p$ is close to zero) and the successors of k cannot be in progress (i.e., $\alpha_{t,k}^s$ is close to zero).

4.4. Learning Task Graphs

Manually-built task graphs are not always available. We study two methods to obtain the task graph from training videos. Thus, unlike recent works [4, 89] that use the large-scale external knowledge base WikiHow to build the task graph, our method obtains it merely from the training videos, hence, can handle any procedural tasks.

Let $M^p \in \{0, 1\}^{K \times K}$ denote a predecessor indicator matrix, whose (i, j) -th entry is 1 when node i is a predecessor of j . We similarly define a successor indicator matrix, M^s . We can rewrite (7) and (8) in matrix form as

$$\mathbf{A}^p = (\mathbf{1} - \mathbf{C}) \cdot \mathbf{M}^p, \quad \mathbf{A}^s = \mathbf{C} \cdot \mathbf{M}^s, \quad (10)$$

where $\mathbf{C} = [c_{t,k}]$ is the completion state matrix and $\mathbf{A}^p = [\alpha_{t,k}^p]$ and $\mathbf{A}^s = [\alpha_{t,k}^s]$, all being $T \times K$ matrices.

Transcript-based Task Graph. We generate a soft version of the predecessor/successor indicator matrices by computing the frequency of action i occurring before/after action j across the transcripts of training videos. This approach is particularly useful when dealing with large datasets and allows for automated extraction of task dependencies based on observed action sequences. We differ from prior works in text knowledge-based task graph [4, 89] in that we generate task-specific graphs for action segmentation.

Learnable Task Graph. We can also set the predecessor/successor indicator matrix as learnable parameters and automatically update them during training. This approach allows the task graph to adapt and evolve based on the data it processes. We initialize the indicator matrix with the transcript-based task graph, and set a regularization term, i.e., MSE loss, to the initialized matrix and the learnt matrix to avoid trivial solution where all nodes are disconnected. Thus, the learnable graph can be considered as a refinement of the transcript-based graph.

4.5. Learning and Inference

Learning. Our final objective function for training is a combination of classification loss, smoothing loss, progress prediction loss, and task-graph loss,

$$\mathcal{L} = \mathcal{L}_{\text{cls}} + \lambda_{\text{smo}} \mathcal{L}_{\text{smo}} + \lambda_{\text{prog}} \mathcal{L}_{\text{prog}} + \lambda_{\text{graph}} \mathcal{L}_{\text{graph}}, \quad (11)$$

where λ_{smo} , λ_{prog} , λ_{graph} are the weights for the corresponding loss terms. We use Stochastic Gradient Descent (SGD) optimization algorithm to update the parameters in both the action classification and progress regression branches.

Inference. For testing, we input the frames up to time t into our progress-aware causal action segmentation model to get the action logits $o_{t,k}$ of each action class k . Instead of directly applying the Softmax function on action logits to get the probabilities, we leverage the task graph for inference

Method	Inference	GTEA					EgoProceL					EgoPER				
		Acc	Edit	F1@{0.1,0.25,0.5}			Acc	Edit	F1@{0.1,0.25,0.5}			Acc	Edit	F1@{0.1,0.25,0.5}		
Base	Offline	76.3	79.0	85.8	83.4	69.8	69.2	56.9	58.9	55.8	45.9	83.0	85.9	88.9	87.4	77.3
Base	Online	47.0	58.8	64.6	56.3	38.7	18.3	19.9	20.6	15.9	8.8	20.2	31.0	33.3	24.5	11.9
CAS	Online	74.0	64.4	71.8	69.4	56.0	64.5	42.5	45.2	41.6	33.0	71.8	48.9	56.2	52.2	39.4
CAS+OODL [27]	Online	74.0	64.7	70.3	66.9	54.1	66.4	44.0	44.7	41.5	30.5	71.2	49.3	55.6	52.3	40.0
CAS+APP	Online	76.0	67.0	75.1	71.1	57.9	66.3	47.1	49.3	44.9	35.2	72.7	55.0	62.0	58.3	43.4
CAS+APP+TG	Online	74.3	69.2	77.1	74.1	59.7	67.8	48.8	51.5	46.0	35.7	70.2	60.7	65.4	61.2	46.3

Table 1. Performance on three datasets, using MSTCN as the base model.

by subtracting the penalty scores in (7) and (8) from the original logits before feeding them into the Softmax layer:

$$y_{t,k} = \frac{e^{\alpha_{t,k}^p - \eta(\alpha_{t,k}^p + \alpha_{t,k}^s)}}{\sum_{k'} e^{\alpha_{t,k'}^p - \eta(\alpha_{t,k'}^p + \alpha_{t,k'}^s)}}, \quad (12)$$

where the hyperparameter η controls the weight of the task graph at testing. Thus, we use the procedural knowledge to encourage (discourage) online predictions that follow (disobey) the task graph (with high scores for $\alpha_{t,k}^p$ and $\alpha_{t,k}^s$).

5. Experiments

5.1. Experimental Setup

Datasets. We use two established egocentric procedural video datasets: GTEA [23] and EgoProceL [5], as well as the recent EgoPER dataset [46], which focuses on action segmentation and error detection in procedural cooking tasks. EgoPER [46] consists of 213 normal and 173 erroneous egocentric videos, and our study exclusively involves the normal videos. These videos feature different users performing five cooking-related procedural tasks: ‘making coffee’, ‘making pinwheel’, ‘making tea’, ‘making oatmeal’, and ‘making quesadilla’. The videos were captured while the users were equipped with Hololens 2. Each task is associated with a pre-defined task graph that comprehensively encodes all feasible ways to perform the task, and the users were instructed to collect videos according to these variations (see supplementary materials for the task graphs). We also conduct experiments on Assembly101 [66] in the supplementary materials. We observed a lower performance gain on it as the egocentric videos are gray-scale and the steps of assembling small toy parts occur at a very small portion of the view, making it hard to capture progress.

For GTEA, we report the average performance on four splits. EgoProceL consists of egocentric videos from five subsets of different dataset sources, so we train a model on each subset, and report the average performance across all subsets. For EgoPER, we train a model on each task, and report the average performance across all tasks.

Action Segmentation Model. We use MSTCN [22] and ASFormer [85] as our action segmentation backbone. As mentioned in Sec. 4.1, we use causal dilated convolution in MSTCN and causal masking in ASFormer. We use these

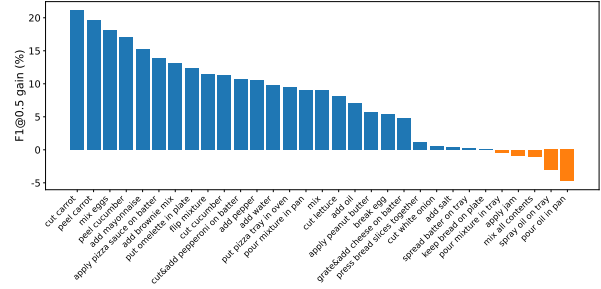


Figure 5. Action-wise improvement gain from APP on EgoProceL.

two popular action segmentation models as our backbone and evaluate the performance gain by our proposed action progress prediction (APP) module and task graph (TG). We did not use MSTCN++ [52] because its dual dilated layer is not beneficial in the context of online action segmentation where future information is not available, although it improves the offline performance over MSTCN. Please see the supplementary for more details.

Implementation Details. We extract 2048-dim features on a window of 32 history frames using I3D [10] pre-trained on Kinetics [10]. Following prior works [22, 83, 85], we evaluate the performance using standard metrics in action segmentation: edit similarity, F1 score with thresholds 0.1, 0.25, and 0.5 (F1@10,25,50), and frame-wise accuracy (Acc). We follow the default setups in MSTCN [22] and ASFormer [85] using their released source codes. For MSTCN, we use four stages and each stage contains ten dilated convolution layers. For the methods with the APP module, we add the progress regression branch at the end of each stage. For ASFormer, we use one encoder and three decoders, and each encoder/decoder contains nine blocks. For the methods with APP, we add the progress regression branch at the end of each encoder and decoder. In all experiments, we train the model using Adam optimizer with a learning rate 0.0005. We train the MSTCN models for 50 epochs and the ASFormer models for 120 epochs.

5.2. Experiment Results

Online Action Segmentation. Table 1 and Table 2 show the results of using MSTCN and ASFormer, respectively, as the base models. We begin by using the base model for training and testing an offline action segmentation model,

Method	Inference	GTEA					EgoProceL					EgoPER				
		Acc	Edit	F1@{0.1,0.25,0.5}			Acc	Edit	F1@{0.1,0.25,0.5}			Acc	Edit	F1@{0.1,0.25,0.5}		
Base	Offline	83.4	84.6	89.7	88.8	78.9	69.5	59.8	63.0	59.7	48.8	81.8	88.8	90.4	89.2	79.9
Base	Online	36.2	48.2	52.5	44.4	28.3	13.2	17.6	13.3	9.8	5.4	19.8	24.3	25.7	16.2	8.8
CAS	Online	77.2	73.3	79.6	77.1	65.0	64.8	48.1	49.8	45.0	35.4	70.3	60.6	66.1	62.3	44.7
CAS+APP	Online	77.3	74.0	79.9	77.3	65.4	66.7	50.7	51.0	47.1	36.1	70.6	61.2	67.9	63.6	46.9
CAS+APP+TG	Online	77.0	74.1	80.2	77.5	66.1	68.5	52.1	51.6	48.9	36.8	71.7	62.4	68.8	65.9	48.6

Table 2. Performance on three datasets, using ASFormer as the base model.

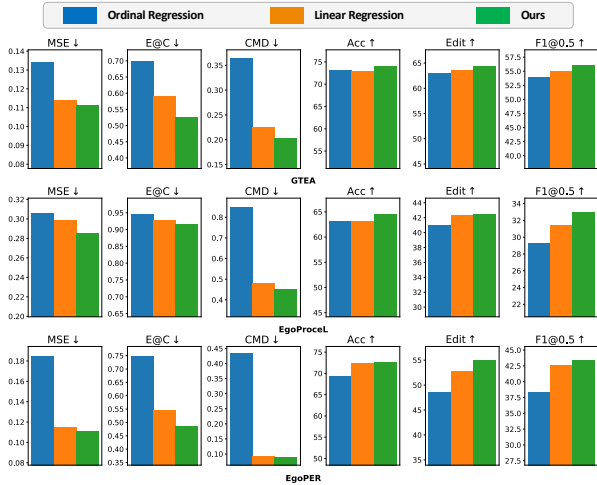


Figure 6. Comparison of different model designs for action progress prediction (APP) on GTEA (top), EgoProceL (middle) and EgoPER (bottom).

which sets the *upper bound* for online models. Then we employ the offline-trained base model for online inference. More specifically, every time a new frame arrives, we input all history frames into the model to make predictions at the current frame. The results reveal a huge gap between online and offline inference, e.g., Acc drops from 69.5% to 13.2% on EgoProceL and from 81.8% to 19.8% on EgoPER for the ASFormer base and similarly for MSTCN base. This underscores the significance of and the need for a well designed online action segmentation model.

To bridge this gap, we first use our Causal Action Segmentation (CAS) models. These models keep consistency during both training and inference, ensuring that no future frames are utilized. The results demonstrate a remarkable improvement compared to performing online inference using an offline-trained base model. For example, the F1@0.5 improves from 8.8% to 33.0% on EgoProceL and from 11.9% to 39.4% on EgoPER for the MSTCN base (similarly for ASFormer base). Next, we investigate the impact of our Action Progress Prediction (APP) and leveraging our transcript-based Task Graph (TG) for online action segmentation. APP consistently improves the performance in all metrics on three datasets, e.g., improves the F1@0.5 by about 4% on both EgoProceL and EgoPER in Table 1. Although on GTEA, the frame-wise accuracy slightly decreases when incorporating the task graph, we noted im-

provement in edit similarity and F1 scores. These metrics are based on the predicted segments and penalize over-segmentation, which suggest that leveraging our estimated task graph reduces oversegmentation, resulting in smoother and procedure-consistent online predictions. Overall, using our framework brings the online segmentation performance much closer to the offline segmentation.

Ghodoosian et al. [27] introduced an Online-Offline Discrepancy Loss (OODL) for weakly-supervised online action segmentation. OODL runs online and offline inference separately and uses the offline results to supervise the online model. Inspired by it, we simultaneously train two models, one causal and one non-causal model, and minimize the difference between their predictions to reduce the online-offline discrepancy. However, as the results show, adding OODL does not help the performance in fully-supervised online action segmentation, as the ground-truth framewise label is already used during training. In fact, adding an offline segmentation model as the teacher model does not perform better than directly using the ground-truth.

Action-wise performance. We evaluate the action-wise performance to investigate how APP is helpful for online segmentation in Figure 5. Interestingly, we notice that estimating progress is more helpful to the actions related to huge appearance change through the course of the action, e.g., “cut carrot”, “peel cucumber”, etc. On the contrary, the appearance change of actions like “pour oil in the pan” may not be very visible in the videos, and actions like “mix all the contents” do not have a good definition for progress, so APP is not effective in those cases.

Performance of Action Progress Prediction Module. We evaluate the effects of different designs for our APP model. We compare our proposed design with two variants: 1) ordinal regression [9, 37, 60]; 2) linear regression without the GRU layer. To evaluate the progress estimation, we use three metrics: 1) MSE between the predicted progress and ground-truth progress for each action segment; 2) E@C (error at completion), the absolute error between the predicted progress and ground-truth progress at the completion moment; 3) CMD (completion moment difference), the difference between the normalized time of completion moments in predictions and ground-truth, and the completion moment is defined as when the progress reaches its peak. The results are shown in Figure 6. We notice that Ordinal

Dataset	Method	Acc	Edit	F1@{0.1,0.25,0.5}		
GTEA	transcript	74.3	69.2	77.1	74.1	59.7
	learnable	74.5	69.3	77.2	74.3	60.2
EgoProceL	transcript	67.8	48.8	51.5	46.0	35.7
	learnable	68.0	48.9	51.4	45.5	34.8
EgoPER	transcript	70.2	60.7	65.4	61.2	46.3
	manual learnable	70.4	61.0	65.8	61.3	46.5
		70.6	61.4	67.1	62.3	47.1

Table 3. Performance of different choices of building the task graph.

Regression is not performing well for modeling progress, leading to high errors in progress estimation and degrading the action segmentation performance. Compared with Linear Regression without the GRU layer, our choice performs better in both progress prediction and online action segmentation due to smoother predictions.

Ablation Studies on the Task Graph. In Table 3, we compare different ways of obtaining the task graph. On GTEA and EgoProceL, we compare transcript-based task graph with learnable task graph, discussed in Sec. 4.4. Since we have manually built task graphs on EgoPER, we additionally evaluate the performance of using manually designed task graphs. Overall, the learnable task graph performs better. On EgoPER, the manually designed task graph performs slightly better than the transcript-based task graph. The slight gap indicates that our transcript-based task graph can already well capture the dependency in procedural activities, and serve as a good proxy when the manual task graph is not available. Besides, the learnable task graph, initialized from the transcript-based or manual graph, is able to further improve the performance on GTEA and EgoPER, showing that the model is able to learn a probabilistic graph more specific to the videos through training. We notice that the learnable task graph does not yield improvements on EgoProceL. This could be attributed to the substantial variation in procedures within this dataset. The model might face challenges in learning a suitable probabilistic graph given the extensive diversity observed in the training videos.

Offline Action Segmentation. While we introduced the APP and TG for online action segmentation, we also investigated their impacts in the context of offline action segmentation in Table 4. While APP and TG can enhance the segmentation results in some cases, the improvement is less significant compared with their impacts in online scenarios. This is because the offline model is able to consider the future frames to correct the prediction errors without the need of modeling the action progress or using task graph. See the supplementary materials for results on other datasets.

Qualitative Results. Figure 7 visualizes the predictions by various models on two videos from EgoPER. The first one from the task “making oatmeal” uses MSTCN as the backbone while the second one from the task “making tea” uses ASFormer. Notice that directly applying the offline trained model to the online inference setting causes a huge performance drop due to the discrepancy between training and in-

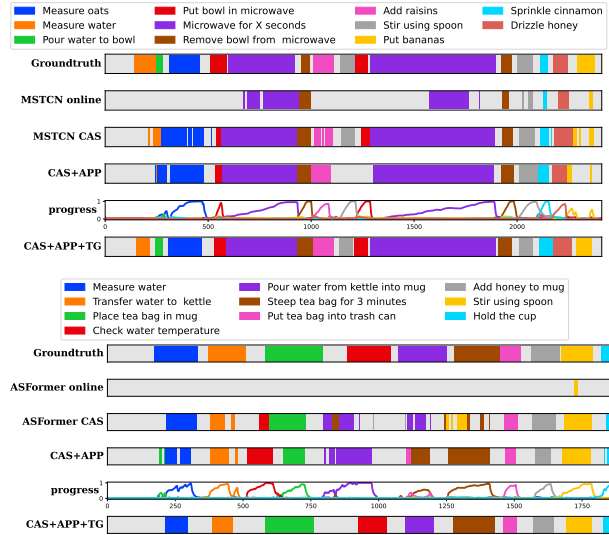


Figure 7. Visualization on the online predictions and progress estimation.

Method	Acc	Edit	F1@{0.1,0.25,0.5}		
MSTCN	69.2	56.9	58.9	55.8	45.9
MSTCN+APP	70.3	56.6	60.6	56.9	46.8
MSTCN+APP+TG	71.1	60.4	63.3	59.3	46.1

Table 4. Offline action segmentation performance on EgoProceL.

ference. Using the proposed CAS model significantly mitigates this issue, yet, we still see oversegmentation in predictions. By adding the APP module, the model learns to estimate the action progress and reduces oversegmentation. However, CAS+APP may still make erroneous predictions that are inconsistent with the task graph. In the first example, CAS+APP fails to correctly detect the step “measure water” and “pour water to bowl” before “put bowl in microwave”. In the second example, CAS+APP predicts “put tea bag into trash can” before “steep tea bag for 3 minutes”. By incorporating the task graph, the model leverages high-level knowledge and correctly recognizes these steps.

6. Conclusions

We proposed a progress-aware online action segmentation framework. We bridge the gap between offline training and online inference via causal action segmentation model, and improve online segmentation by estimating the progress of online actions via APP module. Further, we leverage the high-level procedural knowledge by learning task graphs from training videos themselves. Our framework reduces prediction uncertainty and oversegmentation, and achieves notable improvements on three egocentric video datasets.

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