Contrastive Learning for Improving ASR Robustness in Spoken Language Understanding

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Abstract
Spoken language understanding (SLU) is an essential task for machines to understand human speech for better interactions. However, errors from the automatic speech recognizer (ASR) usually hurt the understanding performance. In reality, ASR systems may not be easy to adjust for the target scenarios. Therefore, this paper focuses on learning utterance representations that can robustly handle speech-related errors and further strengthens the generalization ability by combining supervised contrastive learning and self-distillation in model fine-tuning. Experiments on three benchmark datasets demonstrate the effectiveness of our proposed approach.

Index Terms: spoken language understanding, contrastive learning, self-distillation, robustness.

1. Introduction
Intelligent agents such as Apple Siri, Amazon Alexa, and Google Assistant are flourishing with recent advances in speech technology. The core element in these agents is spoken language understanding (SLU), which takes human speech input and extracts semantic information for various tasks, such as intent classification and slot filling. Existing SLU solutions can be categorized into two types: 1) pipeline (or cascade) approaches and 2) end-to-end approaches. Pipeline approaches first use automatic speech recognition (ASR) system to transcribe speech into text, followed by a natural language understanding (NLU) component for the target task, while end-to-end approaches [1] apply a single model which can directly process speech signals and handle the understanding task without considering the text.

Pipeline approaches take many benefits from using textual information: it would be easier to utilize additional resources including large-scale datasets and pre-trained models from the NLP community, relieve the burden of ASR development, and prevent privacy issues about using human voices. However, pipeline methods usually suffer from error propagation – when the ASR hypothesis is incorrect, the erroneous text can mislead the NLU model and hurt the performance. Although ASR systems today have already reached a low word error rate (WER) on data in a controlled environment, a real-world environment still leads to unsatisfied performance. Researchers have explored remedies for ASR errors in two ways: either formulating the ASR error correction as a machine translation from erroneous ASR hypothesis to clean text [2, 3, 4] or adapting the model through masked language modeling (MLM) [5, 6, 7]. Most prior approaches required additional speech-related input features such as phoneme sequences [3, 4, 5], lattice graph [7, 8, 9], or N-best hypothesis [10, 11, 12]. Such information may not be easily obtained due to the constraint of ASR systems.

With the rise of BERT [13], pre-trained language models (PLMs) have been dominating the field of NLP. While it is straightforward to adopt PLM in pipeline SLU systems, PLMs are often trained on clean text corpus and thus not resistant to ASR errors. In order to learn the invariant representations between manual transcript and erroneous hypothesis, this paper proposes to utilize a contrastive objective to adapt PLM to ASR results with only textual information.

Contrastive learning aims at pulling together the feature similarity of positive data pairs and pushing away negative data pairs [14]. In computer vision, positive and negative samples are mostly derived from data augmentation, but due to the characteristics of discreteness in texts, the NLP community does not have a common strategy to create multiple views of a sentence to form positive samples. Prior studies investigated different ways to construct positive pairs, such as back-translation [15], sampling from the same article [16], or the pooled representation from different layers of a model [17]. In spoken scenarios, we naturally take a manual transcript and its associated ASR hypothesis as a positive pair and maximize the similarity between their representations, because they come from the same audio signal. Thus, the learned representations can be more error-robust through contrastive learning in pre-training.

In addition, considering the heavily distorted data, we propose a supervised contrastive loss together with a self-distillation strategy during fine-tuning in order to further strengthen the generalization capability. Supervised contrastive learning is a variant of contrastive learning [18], where the positive/negative samples are data with the same/different labels, so the annotated target data is required. Results on both vision [18] and language [19] showed improvement and robustness to inputs noises. Self-distillation [20], or self-knowledge distillation, is a special form of knowledge distillation, where the teacher is the student itself. It simply minimizes Kullback-Leibler (KL) divergence with the model’s previous prediction. Without additional information from another model, self-distillation can still demonstrate the regularization effect and prevent over-confidence. We are the first to combine these two techniques for improving robustness in fine-tuning.

The contributions of this work are four-fold:

- We propose a novel contrastive objective for pre-training models robust to ASR errors. To our knowledge, we are the first to adopt such modeling techniques to improve robustness with only textual information.
- We propose a novel fine-tuning framework combining supervised contrastive learning and self-distillation.
- The proposed method is flexible and can easily incorporate additional information such as phoneme or lattice.
- Experiments on multiple benchmark datasets demonstrate that the proposed approach is capable of handling noisy text inputs and achieves significant improvement.

The codes are released in this github repository https://github.com/MiuLab/SpokenCSE.
2. Methodology

Our proposed method consists of three elements: (1) A self-supervised contrastive objective for pre-training, (2) supervised contrastive learning, and (3) self-distillation in fine-tuning.

2.1. Self-supervised contrastive learning

Contrastive learning aims at helping our model distinguish the features invariant to input transformations, including data augmentations and corruptions. To handle ASR errors, we propose to adopt contrastive learning for learning sentence representations invariant to misrecognition. As shown in Figure 1, a pre-trained RoBERTa [21] is continually trained on spoken language corpus by utilizing the paired clean and noisy sentences.

Given a mini-batch of input data of \( N \) pairs of texts \( B = \{(x_i^{clean}, x_i^{asr})\}_{i=1..N} \) representing the clean manual transcript and ASR hypothesis. We first apply the pre-trained BERT and contrastive learning losses (hard and soft) to obtain the representation for sentence representations by the proposed self-supervised contrastive loss [14, 22]:

\[
L_c = \frac{1}{2N} \sum_{(h, h^+)} \log \frac{e^{s(h, h^+)/\tau_c}}{\sum_{h' \neq h} e^{s(h, h')/\tau_c}}
\]

\[
= -\mathbb{E}_{x_i^{clean}} \left[ \log \frac{e^{s(h, h^+)/\tau_c}}{\sum_{h' \neq h} e^{s(h, h')/\tau_c}} \right]
\]

(1)

where \( \mathbb{P} \) is composed of \( 2N \) positive pairs of either \((h_i^{clean}, h_i^{asr})\) or \((h_i^{asr}, h_i^{clean})\), and \( s(\cdot, \cdot) \) is a cosine similarity function. The process is illustrated in Figure 1.

Among two terms in the second line of (1), the first term improves the alignment between positive pairs with robustness to noise, and the second term promotes uniformity in representation space by pushing away features of unrelated samples [23]. Both are known as good characteristics of representations and improve generalization.

To prevent catastrophic forgetting of the PLM, we keep the MLM objective in the pre-training process. Additionally, the prior work revealed the advantage of adaptive pre-training on the same domain of the downstream data [24], so the final proposed pre-training loss \( L_{pt} \) is the weighted sum of a contrastive loss \( L_c \) and an MLM loss \( L_{mlm} \):

\[
L_{pt} = L_c + \lambda_{mlm} \cdot L_{mlm},
\]

(2)

where \( \lambda_{mlm} \) is a weight to maintain the model’s ability of predicting the masked tokens.

2.2. Supervised contrastive learning

Supervised contrastive learning at fine-tuning takes data of the same label as positive samples and pulls their embeddings closer together [18]. In the end, the representations from the same label form a clustering effect and discriminate over different labels by creating margins between them. This objective is similar to the widely-used triplet loss [25], but it can generalize to more than one positive and negative sample and is empirically shown to improve performance and robustness to input noises [19]. We propose to adopt a supervised contrastive loss \( L_{hard} \) to allow the learned representations aligned with their hard labels as illustrated in Figure 2:

\[
L_{hard} = \frac{1}{N} \sum_{i=1}^{N} \sum_{j=1}^{N} 1_{y_i = y_j} \log \frac{e^{s(h_i, h_j)/\tau_c}}{\sum_{k \neq i} e^{s(h_i, h_k)/\tau_c}}.
\]

(3)

2.3. Self-distillation

Due to ASR errors, some input sentences may no longer retain the semantics of their labels, or shift to some fluent context of another class. For example, when on is transcribed into off in an IoT control command, the intent can be the exact opposite. Therefore, in order to reduce the impact of label noises in the training set, we propose a self-distillation method.

Self-distillation minimizes KL divergence between the current prediction and the previous one [26, 27], which regularizes the model and eliminates label noise at the same time. We denote \( p_i^t = \hat{P}(y_i | x_i) \) as the probability distribution of data \( x_i \) predicted by the model at the \( t \)-th epoch, and its loss function is formulated as:

\[
L_d = \frac{1}{N} \sum_{i=1}^{N} KL_{ct}(p_i^{t-1} || p_i^t),
\]

and \( p_i^0 \) is a one-hot vector of the label \( y_i \). This procedure is illustrated in the right part of Figure 2.

2.4. Self-distilled soft contrastive learning

To relieve the effect of noisy labels in supervised contrastive learning, we add a supplement loss similar to (3) by contrasting the soft label calculated from the previous prediction:

\[
L_{softf} = \frac{1}{N} \sum_{i=1}^{N} \sum_{j=1}^{N} 1_{y_i = y_j} \log \frac{e^{s(h_i, h_j)/\tau_c}}{\sum_{k \neq i} e^{s(h_i, h_k)/\tau_c}}.
\]

(5)

This soft target strategy is also investigated in recent self-supervised contrastive learning studies such as ReSSL [28] and SCE [29], where the soft target comes from the similarity between their samples. In the framework shown in Figure 2, our finalized fine-tuning loss \( L_{ft} \) composes of four parts: 1) a cross entropy loss in the original fine-tuning stage \( L_{ce} \), 2) two contrastive learning losses (hard \( L_{hard} \) and soft \( L_{softf} \)) and 3) a self-distillation loss \( L_d \) shown as below:

\[
L_{ft} = L_{ce} + \lambda_d L_d + \lambda_{sc}(L_{hard} + \lambda_d L_{softf}).
\]

(6)

3. Experiments

3.1. Datasets

Three benchmark datasets are used for evaluating our model: SLURP [30], and two synthesized datasets ATIS and TREC6 from PhoneME-BERT [5]. The statistics are shown in Table 1.
SLURP is a challenging SLU dataset with various domains, speakers, and recording settings. This paper only focuses on intent detection, where an intent is a (scenario, action) pair, and there are 18 scenarios and 46 actions in total, and the joint accuracy is used as the evaluation metric (both scenario and action are correct). We use two off-the-shelf ASR systems to obtain ASR hypothesis from the provided audio: Google Web API and wav2vec 2.0 [31]. The median word error rate (WER) is 25% by Google and 60% by wav2vec, implying the difficulty of performing SLU tasks using ASR hypothesis due to diverse accented speakers and noisy environments in this dataset. Through manual inspection, we find some noisy or incorrect labels in SLURP shown in Table 2, so we sub-sample a test set to ensure its quality for reliable evaluation. Note that the training set may still contain label noises, so the model’s robustness to label noises can be still validated in our experiments.

ATIS and TREC6 are two benchmark datasets for flight reservation and question classification respectively. We use the synthesized text released by Phoneme-BERT [5], where the data is synthesized via a TTS model and later transcribed by ASR. Only a subset of data within a certain WER range is kept, and the reported average WER is 29.11% for ATIS and 32.03% for TREC6. We report accuracy as the evaluation metric (both scenario and action classification heads are trained for scenario and action with early stopping and a batch size 256. In SLURP, two separate classification heads are trained for scenario and action with shared BERT embeddings. We grid search over hyperparameters by metrics of validation set and find that the model is not sensitive, and the final setting is that the mask ratio of MLM is \( \tau_c = 0.2, \lambda_{mlm} = 1, \tau_a = 0.2, \lambda_a = 0.1, \tau_d = 5, \lambda_d = 10. \) The reported scores are averaged over 5 runs.

### 3.3. Evaluation results

The evaluation performance is presented in Table 3, where three baselines only focus on pre-training for representation learning, so we additionally show the results only using our proposed pre-training method. The results demonstrate that the proposed contrastive learning in pre-training is useful for handling ASR noises and achieves better performance in most cases. Phoneme-BERT requires additional speech information from phoneme sequences to boost the performance and thus less effective on SLURP, while our model only takes word-level information. Moreover, the proposed fine-tuning framework with contrastive learning and self-distillation further models the uncertainty and improves the performance. In summary, our proposed method is demonstrated effective for SLU and outperforms all baselines on three benchmark datasets.

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**Table 1: Dataset statistics. SLURP test is sub-sampled.**

| Dataset | #Class | Avg. Length | Train | Test |
|---------|--------|-------------|-------|------|
| SLURP   | 18 × 40| 6.93        | 50,628| 10,992|
| ATIS    | 22     | 11.14       | 4,978 | 893  |
| TREC6   | 6      | 8.89        | 5,452 | 500  |

**Table 2: Label noises in SLURP (mislabeled and ambiguous). Model prediction is generated by a fine-tuned RoBERTa.**

| Transcripts                  | Label                  | Prediction          |
|------------------------------|------------------------|---------------------|
| hello how is your day        | (general, quirky)      | (general, greet)    |
| let’s play music hits        | (play, radio)          | (play, music)       |
| what date is it              | (calendar, query)      | (datetime, query)   |

**Table 3: Results on three datasets. Phoneme-BERT\(^1\) additionally uses phoneme sequences generated by public tool-kit.**

| Model               | SLURP | ATIS | TREC6 |
|---------------------|-------|------|-------|
| RoBERTa             | 83.97 | 94.53| 84.08 |
| Phoneme-BERT\(^1\)  | 83.78 | 94.83| 85.96 |
| SimCSE              | 84.47 | 94.07| 84.92 |
| Proposed (pre-train only) | 84.51 | 95.02| 85.20 |
| Proposed (pre-train + fine-tune) | **85.26** | **95.10**| **86.36** |

\(^1\)We use facebook/wav2vec2-large-960h trained on LibriSpeech provided on HuggingFace [32].

\(^2\)This is phoneme-BERT trained on LibriSpeech.

\(^3\)https://github.com/bootphon/phonemizer
Table 4: Result on SLURP. WER intervals are separated by quartiles. The reported metric is joint accuracy. Phoneme-BERT uses input text with additional toolkit-generated phoneme sequences.

| Pre-training  | Fine-tuning | SLURP WER Interval (Google) | SLURP WER Interval (wav2vec) |
|---------------|-------------|-----------------------------|-----------------------------|
|               |             | clean =0 | low (0.16) | medium (0.16-0.4) | high >0.4 | all [0.25] | medium (0.25-0.5) | high (0.5-0.83) | severe >0.83 | all |
| RoBERTa       | Direct      | 95.69   | 92.41   | 85.89   | 56.71   | 83.97   | 92.44   | 80.49   | 62.06   | 34.40   | 68.05    |
| Phoneme-BERT  | Direct      | 94.97   | 92.34   | 85.87   | 57.20   | 83.78   | 91.40   | 79.71   | 62.60   | 36.56   | 68.24    |
| SimCSE        | Direct      | 95.55   | 93.47   | 86.82   | 57.59   | 84.47   | 92.04   | 81.75   | 62.98   | 34.25   | 68.48    |
| Proposed      | Direct      | 95.54   | 93.86   | 86.68   | 57.72   | 84.51   | 93.02   | 82.56   | 64.22   | 36.02   | 69.66    |
| Phoneme-BERT  | Proposed    | 96.59   | 94.27   | 86.70   | 57.24   | 84.87   | 93.56   | 81.59   | 63.29   | 34.61   | 68.98    |
| SimCSE        | Proposed    | 96.57   | 94.54   | 87.39   | 58.01   | 85.25   | 92.62   | 80.86   | 62.13   | 33.25   | 67.94    |
| Proposed      | Proposed    | 96.08   | 94.41   | 87.63   | 58.72   | 85.26   | 93.76   | 83.43   | 65.31   | 35.83   | 70.31    |

3.4. Analysis of different noise levels

To better investigate the impact of different noise levels, we separate the test set of SLURP into 4 groups according to their WER and show the performance in Table 4. From the upper part of Table 4, our proposed pre-training procedure consistently outperforms all baselines for most cases except clean and severe noise levels. When the input is clean, treating SLU as normal NLU is better, so the original RoBERTa performs best. SimCSE pre-training achieves similar performance with relatively lower WER, but cannot generalize to noisier inputs when we use wav2vec transcripts. Because our proposed self-supervised contrastive learning method allows the model to learn the invariant features by utilizing the relationship between ASR and manual transcripts, the learned spoken representations can be robust even to much noisy inputs. From the lower part of Table 4, our proposed fine-tuning procedure can further boost the performance regardless of pre-trained methods, showing the effectiveness of our framework combining supervised contrastive learning and self-distillation.

3.5. Ablation study

Because the proposed method is composed of multiple elements, we conduct an ablation study to further investigate the effect of each loss in Table 5. The results show that each proposed method (for pre-training and fine-tuning) contributes to the performance positively. It is obvious that MLM in pre-training and self-distillation in fine-tuning play an important role, because MLM pre-training is crucial to adapting the PLM to noisy inputs, and self-distillation prevents the model from overfitting the mismatched text and label pairs. Moreover, self-distillation also reduces the impact of label noises in SLURP and thus brings more contribution.

3.6. Analysis of exploiting manual transcripts

In our proposed procedure, we pre-train on the paired ASR and manual transcripts via contrastive learning. Such information can be exploited in other ways; for example, we can pre-train a sequence-to-sequence model for correcting ASR hypothesis to its manual transcript, and then the encoder can be used in the fine-tuning stage. The upper part of Table 6 shows that the proposed approach can better utilize the paired signal and achieves better performance. One possible reason is that the limited paired data is insufficient for correcting ASR results, while our proposed contrastive learning does not focus on fine-grained text correction but on representation distance for great effectiveness and better efficiency.

Furthermore, our experiments assume that only ASR results are available during fine-tuning for better practice, because the original audio signal may not be manually transcribed for privacy issues. If both manual and ASR transcripts are available in the downstream task, we can also fine-tune the model on both types of data. The lower part of Table 6 shows that additionally utilizing manual transcripts in fine-tuning is beneficial, but taking ASR transcripts is necessary to align with the target inference scenario. Future work can consider how to deal with the scenarios when only clean sentences are available. Also, even without SLU data, our proposed method can still utilize any speech corpus with off-the-shelf ASR in our pre-training stage. Hence, our future work is to validate if other available large speech corpus can further improve the robustness of ASR through our proposed method.

4. Conclusions

This work introduces a novel contrastive objective for learning ASR-robust representations and utilizes supervised contrastive learning and self-distillation to better handle the uncertainty and prevent overfitting. To our knowledge, we are not only the first to utilize contrastive learning for modeling the invariant features between manual and ASR transcripts but also the first to combine self-distillation with supervised contrastive learning for better handling uncertainty. Experiments on three benchmark datasets demonstrate the effectiveness of the proposed framework, showing the great potential of bridging the gap of understanding performance between clean and noisy inputs.

Table 5: Ablation study of different losses (%).

| $\mathcal{L}_{pt}$ | $\mathcal{L}_{ft}$ | SLURP | ATIS | TREC6 |
|-------------------|-------------------|-------|------|-------|
| full              | full              | 85.26 | 95.10| 86.36 |
| no $\mathcal{L}_{mlm}$ | full              | 84.83 | 93.75| 85.32 |
| no $\mathcal{L}_{c}$ | full              | 85.15 | 95.00| 85.52 |
| full              | no $\mathcal{L}_{hard} + \mathcal{L}_{soft}$ | 85.14 | 94.83| 86.08 |
| full              | no $\mathcal{L}_{s} + \mathcal{L}_{soft}$ | 84.77 | 94.75| 85.60 |
| full              | no $\mathcal{L}_{soft}$ | 84.81 | 94.65| 86.20 |

Table 6: Results on SLURP with parallel data in different ways.

| Pre-train Method | Fine-tune Data | Accuracy |
|------------------|----------------|----------|
| ASR Correction   | ASR            | 83.96    |
| Proposed         | ASR            | 85.26    |
| Proposed         | Manual         | 84.82    |
| Proposed         | Manual + ASR   | 85.64    |
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