様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科研費 KAKENHI

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研究課題名（和文）Domain adaptation for acoustic inspection of concrete structures

研究課題名（英文）Domain adaptation for acoustic inspection of concrete structures

研究代表者
ルイ笠原　純ユネス（Louhi Kasahara, Jun Younes）

東京大学・大学院工学系研究科（工学部）・特任講師

研究者番号：２０８８５４１２

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研究成果の概要（和文）：コンクリート構造物は、現代社会における建築物の大部分を占め、特に社会インフラに当てはまる。定期的な検査は市民の安全を確保するために非常に重要である。打音検査は、音響を利用した検査方法で、現在普及している。検査を必要とするコンクリート構造物の増加と人手不足の間で、打音検査の自動化が強く望まれている。
近年、機械学習モデルは認識タスクにおいて優れた性能を示した。しかし、その多くは大量のラベル付き学習データを必要とする。これは、打音のようなニッチなアプリケーションでは実現不可能である。そこで本研究では、モデルが利用可能な訓練データとは無関係に優れた性能を発揮できるようにする方法に焦点を当てた。

研究成果の学術的意義や社会的意義
Several avenues were considered. Multi-modal domain adaption, domain expansion and domain independent data extraction. Those work on different levels and great results were obtained for each. In the future, their integration into a single framework for a working system could be considered.

研究成果の概要（英文）：Concrete structures make up a large portion of buildings in modern societies. This is especially true for social infrastructures (tunnels, bridges, highways,...). Their regular inspection is critical to ensure the safety of the public. The hammering test is an inspection method based on acoustic means that is currently popular but is man-power heavy. Between the growing number of concrete structures in need of testing and the man-power shortage, the automation of the hammering test is highly desirable.
In recent years, machine learning models have made great strides, showing great performance on recognition tasks. However, most require large amounts of labeled training data to do so. This is not feasible for niche applications such as the hammering test. Therefore, this research has focused on ways to allow models to perform well independently of the available training data.

研究分野：知能ロボティクス関連

キーワード：Inspection　Domain adaptation　Clustering　Weak supervision　Machine learning　Non-destructive testing

１．研究開始当初の背景

Fig. 1: A human inspector conducts the hammering test in a tunnel.

Heavy use of concrete as a construction material is often cited as a characteristic of modern societies. This is particularly true for social infrastructures such as highways, bridges, and tunnels. In recent years, the issue of the aging of such structures has been highlighted by catastrophic accidents: the collapse of the Sasago tunnel in Japan or of the Big Dig in Boston can be mentioned here as examples. In order to ensure the continued safe use of such social infrastructures made out of concrete, regular inspection to find defects as early as possible is critical. The hammering test, as shown in Fig.1, is a widespread inspection method for concrete structures. It consists in hitting the structure with a hammer and assessing the presence of defects from the returned sound. Manpower shortage and the ever- growing number of structures in need of testing have made the automation of the hammering highly desirable.

Automation of the hammering test has challenges that can be divided between those related to the processing of the complex acoustic data that is currently analyzed by skilled human inspector and those related to the actual hammering mechanism itself to replicate how human inspectors hit the surface of the concrete. This present research focused on the former.

２．研究の目的

Current approaches to automatically analyze hammering sounds are mainly limited to supervised learning. This means that they present first the issue of requiring gathering training data first. This is very costly for such specific applications. Additionally, such approaches limit the applicability of the trained model to the data distribution of the training data. Given that concrete is an aggregate, i.e., no two concrete batches are identical, and that structures vary greatly in shape and form, this severely limits the range of inspection targets over which a trained model is applicable. This is referred to as the *domain* of a model in this research. It can be thus argued that they lack practicability. Therefore, in this research were explored several avenues in which to realize the automation of the hammering test in a fashion to adapt the domain of defect detection models.

３．研究の方法

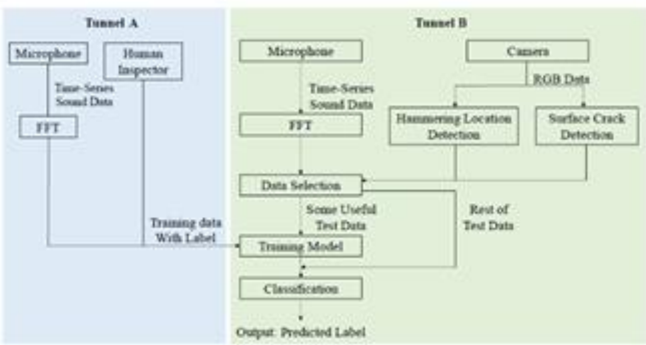

Fig. 2: Overview for the multi-modal domain adaptation method.

Semi-Supervised Support Vector Machine (S3VM) is a semi-supervised learning model that learns a decision boundary based on both labeled training and unlabeled test data. This can be applied to domain adaptation by using training data from a concrete structure A and test data from a concrete structure B. In this research, the framework of S3VM was expanded by the addition of a selection process when using test data to train the model. As shown in Fig. 2, only part of the data is used to adapt a model across domains. To achieve that, in this research the surface crack was used: by using a camera to record the hammering process and thus the hammering location along with the hammering sound, sound samples in the vicinity of a surface crack can be selected to be used by S3VM. This provides the algorithm with samples with a clear separation between them to adapt the decision boundary from the labeled training data.

The domain of a model can also be expanded, in the hopes that the expansion would cover the test data. One method to do so is through data augmentation. While most data augmentation is carried out on the data itself, in this research focus was put on augmenting weak supervision. Weak supervision refers here to pairs of samples a human would indicate as similar or dissimilar. Based on such hints provided by a human, the feature space in which separation between defect and non-defect hammering samples is to be conducted can be shaped into a feature space that matches more closely the vision of the human, i.e., a feature space more suited for the separation. In this research this is conducted using Relevant Component Analysis (RCA), which is basically a biased whitening process limited to groups of samples that could be inferred to belong to the same class. Performance of such approaches is conditioned by the size of those groups of samples. However, obtaining such a large group of samples requires more weak supervision and thus more human involvement. The concept here lies in augmenting weak supervision based on an initial fine clustering of the data, which allows to augment the nature of weak supervision from pair-based to group-of-sample-based.

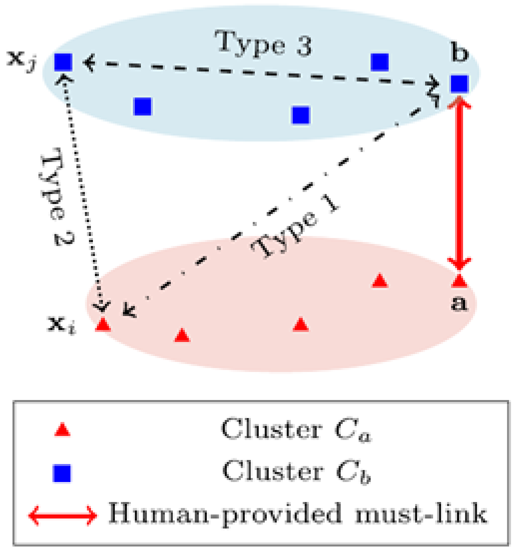

Fig. 3: Concept for the proposed method to augment the initial pairwise weak supervision (in red) to include additional, new knowledge (relationship Types 1 to 3)

Since the hammering test is an acoustic method, one issue that severely affects its performance is the presence of acoustic noise. Acoustic noise is largely dependent on the considered environment and can be considered as a unique characteristic. This exacerbates the issue of transferring models between domains further since it binds data to a particular structure and environment. This issue has been increasingly put forward due to the attention to the potential for Unmanned Aerial Vehicles (UAVs) to carry out the hammering test. The main source of noise in the environment is thus the UAV's propellers. To obtain domain independent data from am UAV conducting hammering, the proposed method takes the innovative approach of multi-modal learning to predict the noise mixed in with the hammering data, as shown in Fig. 4. This is achieved by affixing accelerometers to the propellers, training a model to predict the corresponding acoustic noise. This is highly practical since no labels are required during the training of the model.

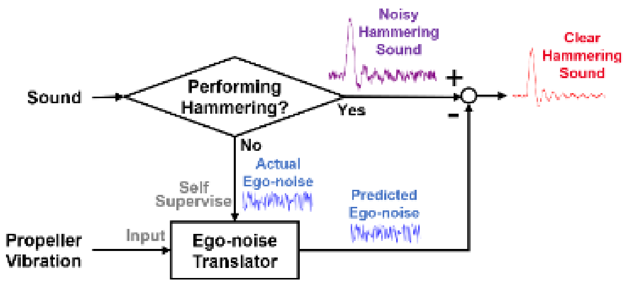

Fig. 4: Overview of the proposed method to remove predicted noise from hammering sounds.

４．研究成果

For the multi-modal domain adaptation, experiments were conducted in laboratory conditions, as shown in Fig. 5, using concrete test blocks, denoted P, Q and R. The results as shown in Fig. 6 show that the proposed method achieves similar or better results than S3VM.

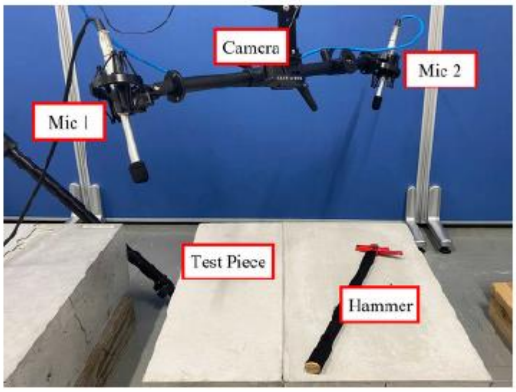

Fig. 5: Experimental settings in laboratory conditions using a concrete test block.

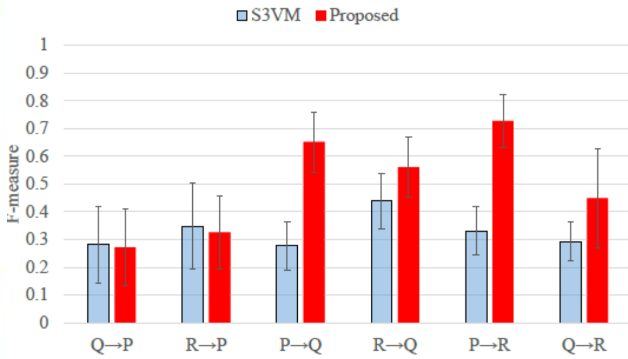

Fig. 6: Result of the proposed method for multi-modal domain adaptation.

For the expansion of domain range with weak supervision, experiments were carried out in both laboratory and field condition, as shown in Fig. 6, and results showed that the proposed method enables to generate new weak supervision automatically high accuracy, ultimately resulting in better model performance with lesser human involvement, as shown in Fig. 7.

Fig. 7: Experimental setup in field conditions using a mock tunnel.

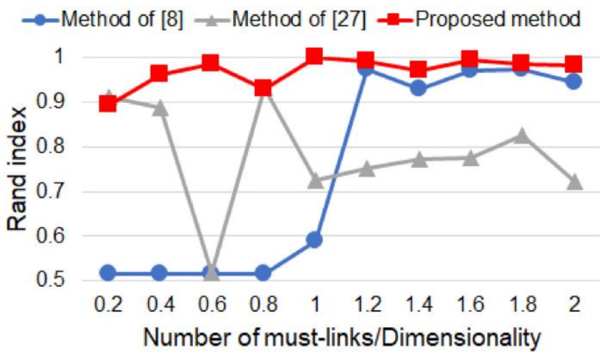

Fig. 8: Results for the method for augmentation of weak supervision. The method shows superior performance with less weak supervision.

For extracting domain independent data, experiments were conducted in laboratory conditions using a real UAV and concrete test blocks. Results, as in Fig. 9, showed that the proposed method enables to accurately predict the noise contained in a recording of hammering acoustic data.

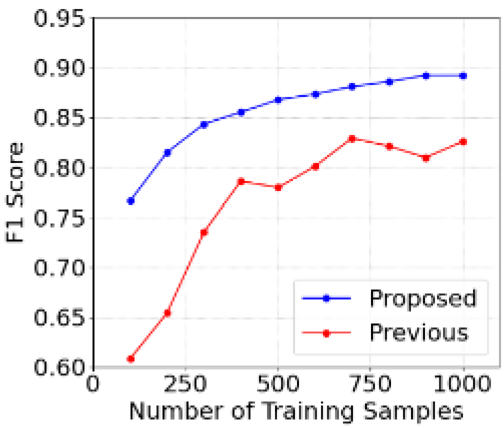

Fig. 9: Performance of the proposed method for noise suppression with predicted noise

５．主な発表論文等

〔雑誌論文〕　計5件（うち査読付論文　4件／うち国際共著　3件／うちオープンアクセス　1件）

１．著者名 Louhi Kasahara Jun Younes、Fujii Hiromitsu、Yamashita Atsushi、Asama Hajime	４．巻 26
２．論文標題 Weakly Supervised Acoustic Defect Detection in Concrete Structures Using Clustering-Based Augmentation	５．発行年 2021年
３．雑誌名 IEEE/ASME Transactions on Mechatronics	６．最初と最後の頁 2826～2834
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TMECH.2021.3077496	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Ushiroda Keitaro、Louhi Kasahara Jun Younes、Yamashita Atsushi、Asama Hajime	４．巻 -
２．論文標題 Multi-modal Classification Using Domain Adaptation for Automated Defect Detection Based on the Hammering Test	５．発行年 2022年
３．雑誌名 Proceedings of the 2022 IEEE/SICE International Symposium on System Integration (SII2022)	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/SII52469.2022.9708607	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Shoda Koki、Louhi Kasahara Jun Younes、Asama Hajime、An Qi、Yamashita Atsushi	４．巻 -
２．論文標題 Ego-Noise Prediction Based on Multimodal Learning for Enhanced Discrimination in UAV Hammering Inspection	５．発行年 2024年
３．雑誌名 Proceedings of the 2024 IEEE/SICE International Symposium on System Integration (SII2024)	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/SII58957.2024.10417712	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 正田 晃己，ルイ笠原 純ユネス，淺間 一，安 琪，山下 淳	４．巻 -
２．論文標題 UAV打音検査における欠陥検知のためのマルチモーダル情報を活用したエゴノイズ低減	５．発行年 2024年
３．雑誌名 第29回ロボティクスシンポジア講演予稿集	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 有
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1．著者名 正田 晃己，ルイ笠原 純ユネス，淺間 一，安 琪，山下 淳	4．巻 -
2．論文標題 Wavelet変換とt-SNEに基づく力覚信号のクラスタリングによるコンクリート構造物の欠陥検知	5．発行年 2024年
3．雑誌名 日本機械学会ロボティクス・メカトロニクス講演会'23講演論文集	6．最初と最後の頁 -
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〔学会発表〕　計4件（うち招待講演　0件／うち国際学会　4件）

1．発表者名 Ushiroda Keitaro
2．発表標題 Multi-modal Classification Using Domain Adaptation for Automated Defect Detection Based on the Hammering Test
3．学会等名 2022 IEEE/SICE International Symposium on System Integration (SII2022)（国際学会）
4．発表年 2021年～2022年

1．発表者名 Shoda Koki
2．発表標題 Ego-Noise Prediction Based on Multimodal Learning for Enhanced Discrimination in UAV Hammering Inspection
3．学会等名 the 2024 IEEE/SICE International Symposium on System Integration (SII2024)（国際学会）
4．発表年 2023年～2024年

1．発表者名 正田 晃己
2．発表標題 UAV打音検査における欠陥検知のためのマルチモーダル情報を活用したエゴノイズ低減
3．学会等名 第29回ロボティクスシンポジア（国際学会）
4．発表年 2023年～2024年

１．発表者名 正田 晃己
２．発表標題 Wavelet変換とt-SNEに基づく力覚信号のクラスタリングによるコンクリート構造物の欠陥検知
３．学会等名 日本機械学会ロボティクス・メカトロニクス講演会'23（国際学会）
４．発表年 2023年～2024年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関