MatGAN: Sleep Posture Imaging using Millimeter-Wave Devices

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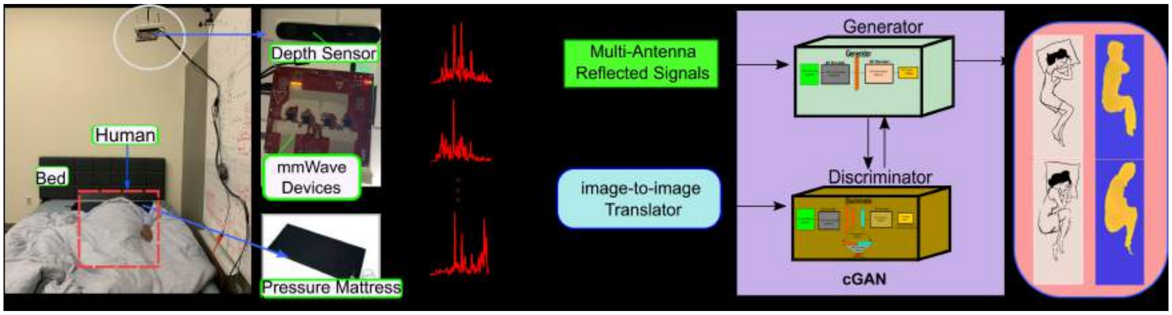

Fig. 1: (a) Experimental setting; (b) Experimental devices; (c) *MatGAN* system architecture; (d) Output of *MatGAN*.

Abstract

This work presents *MatGAN*, a system that uses millimeter-wave (mmWave) signals to capture high-quality images of a person's body while they sleep, even if they are covered under a blanket. Unlike existing sleep monitoring systems, *MatGAN* enables fine-grained monitoring and is privacy non-invasive, and can work under obstruction and low-light conditions, critical for sleep monitoring. *MatGAN* utilizes generative models to generate high-quality images from mmWave reflected signals that accurately represent sleep postures under a blanket. Early results indicate that *MatGAN* can effectively generate sleep posture images with a median IoU of 0.64.

I. Introduction

Our body needs quality sleep to support healthy brain function and to maintain good physical health. Poor sleep is linked to various health issues such as cardiometabolic health problems, Type 2 diabetes, stroke, *etc.* [1]. Therefore, it is important to pay attention to sleep for individuals of all ages and health status, particularly for those with certain health risks. A key factor in evaluating sleep quality is the position in which a person sleeps *i.e.*, sleep posture.

People tend to change positions during sleep, such as lying on their back, stomach, side, or curled up. To prevent serious harm from poor sleep positioning and make it easier for doctors to track a patient's condition, a detailed sleep posture monitoring system is necessary [2]. Therefore, a system that tracks and records body positions would benefit doctors to observe sleep behavior daily without the need for frequent in-clinic visits, which can be costly and inconvenient.

At-home sensors used to monitor sleep can be inconvenient or uncomfortable for users, as they may require the user to wear sensors or place them on the bed, or embed them in textiles. Vision-based systems that use a camera in the bedroom to monitor sleep can invade privacy and are not able to accurately identify sleep postures under blankets or in low light conditions, which are common during sleep. Wireless solutions that are currently available can provide general information about things, such as posture classification and angular orientation, but they are not able to provide detailed, specific information about different parts of the body during sleep due to low resolution. Having fine-grained information, such as imaging or 3D joints, is critical in sleep monitoring as it allows for tracking specific body parts and movements to detect and prevent potentially fatal consequences that may arise from improper sleep postures. The use of high-frequency millimeter-wave (mmWave) wireless signals, which will be more common in the future with the widespread adoption of 5G technology and beyond, could potentially allow for more detailed, fine-grained monitoring. MmWave signals, which have shorter wavelengths (in mm) and can function in low light and through obstructions while preserving privacy, offer a promising solution for non-intrusive sleep posture monitoring.

However, using mmWave signals to monitor sleep postures poses challenges. The human body both reflects and absorbs RF energy resulting in specular and variable reflections, which makes it difficult to discern the positions of body parts and generate full-body images. In addition, mmWave technology has lower resolution compared to systems that use visible light. To address these challenges, traditional imaging algorithms have been proposed but they face the problem of image aliasing due to the limitations of antenna array size and placement, resulting indistinguishable images for distinct postures.

To address these challenges, we propose *MatGAN*, a learning-based system that enables fine-grained monitoring by generating images under a blanket by modeling the relationship between sleep postures and mmWave signals. Further, such high-quality images can be used for joint estimation using the open-source joint estimator module. To obtain the ground truth, we rely on a pressure mattress that provides imaging under the blanket but can only sense the body parts that are in direct contact with the surface of the mattress and does not give the full body information. *MatGAN* has two main components: (1) An image-to-image translator that enables complete ground truth collection; and (2) A custom cGAN (conditional Generative Adversarial Network) that generates sleep posture silhouette images from mmWave reflected signals. We have designed and prototyped *MatGAN* (See 1[b]) using commercial off-the-shelf (COTS) devices, by building 76-81GHz mmWave transceivers to collect reflected signals, a Zed 2i Camera to collect ground truth depth images, and a BodiTrak2 Pressure Mat to collect ground truth pressure images. During deployment, *MatGAN* only requires reflected signals as input to generate images. Our preliminary results show that *MatGAN* can generate sleep posture silhouette images with a median IoU of 0.64 and 90^{th} percentile IoU of 0.83, indicating a close similarity to the ground truth.

II. *MatGAN* Design

We present our overall system design in Figure 1. *First, MatGAN* trains an image-to-image translator to fill in missing information in pressure mattress images and *then,* it uses the collected ground truth to train cGAN by learning the relationship between mmWave reflected signals and sleep postures through thousands of data samples. In runtime, *MatGAN* generates sleep posture silhouette images under the blanket with just mmWave reflected signals as an input.

Image-to-image Translator for Ground Truth Generation: The current method for collecting images of a person's sleep posture while they are under a blanket is using a pressure mattress, but this method only provides incomplete images as it only captures the parts of the body in direct contact with the mattress. We believe the quality of the silhouette images could be further improved by filling in the missing information via learning from other modalities, such as vision-based cameras. Inspired by many previous research works on image-to-image translation or missing data imputation in medical imaging, we propose to use a customized generative model based on the Pix2Pix network [3], which follows the baseline U-net architecture to fill in the missing information.

cGAN for Silhouette Generator: While the image-to-image translator module learns to fill in the missing information in pressure mattress images to provide a ground-truth collection platform, *MatGAN* proposes to overcome fundamental challenges in mmWave imaging via the cGAN framework. From hundreds of controlled human sleep posture experiments, we collect input-output pairs of mmWave reflected signals and pressure mattress images, respectively for different sleep postures. *First,* we improve the quality of pressure mattress images via a pre-trained image-to-image translator to collect complete ground truth. *Then,* the cGAN framework learns the association between the mmWave reflected signals collected from mmWave devices with 192 virtual channels to the 2D ground-truth sleep posture silhouette images via a Generator G and a Discriminator D. Here, Generator is a encoder-decoder network with five 2D convolutional layers and five 2D deconvolutional layers. Convolutional layers in encoder extracts abstract features from the mmWave reflected signals of input size 192×256 with a total of 256 range-reflection bins and deconvolutional layers in decoder converts those features to a 2D sleep posture silhouette images.

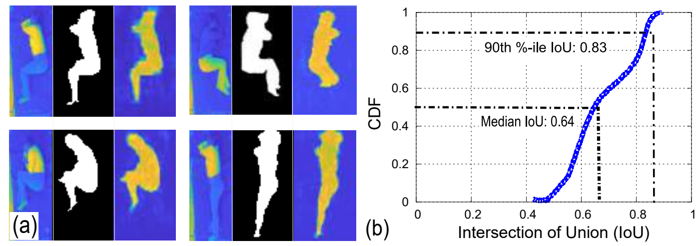

Fig. 2: (a) Sleep posture images (reference, ground truth, and generated). (b) CDF plot of cGAN's performance.

Loss Function: To ensure the optimal convergence of the network, we use vanilla GAN loss function L_G based on the output from the cGAN network during training, along with the mean squared error (MSE) of pixels of generated images with the ground truth images. Total loss is defined as: $L_{Total} = \lambda_1 \cdot L_G + \lambda_2 \cdot L_P$, where λ_1, λ_2 are the hyperparameters to explore to minimize the total loss during training.

III. Preliminary Results

The preliminary evaluation determines the effectiveness of *MatGAN*'s cGAN network in generating high-quality images of sleep from mmWave reflected signals. We collect data from a single volunteer in five different sleep postures, with depth images serving as the ground truth. We collect approximately 5000 training and 3000 test samples, evenly distributed among the postures. We evaluate the performance of the cGAN using Intersection of Union (IoU) to measure the similarity between the generated and ground truth images. Results in Figure 2(a–b) show that the cGAN generates images with a median IoU of 0.64 and a 90^{th} percentile IoU of 0.83, indicating a high level of similarity to the ground truth.

IV. Conclusion and Future Directions

In this work, we propose *MatGAN*, a method for generating high-quality sleep posture silhouette images from mmWave reflected signals. In the future, we plan to design and prototype an image-to-image translator and evaluate the performance of cGAN in diverse settings.

Acknowledgments

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