Slope-assisted fast distributed sensing in optical fibers with arbitrary Brillouin profile

Yair Peled,* Avi Motil, Lior Yaron and Moshe Tur
The Faculty of Engineering, Tel-Aviv University, Tel-Aviv 69978, Israel
yairpeled@gmail.com

Abstract: We present a novel method, based on stimulated Brillouin scattering (SBS), for the simultaneous distributed measurement of fast strain variations along the entire length of the sensing fiber. A specially synthesized and adaptable probe wave is used to place the Brillouin interaction always on the slope of the local Brillouin gain spectrum, allowing a single pump pulse to sample fast strain variations along the full length of a fiber with an arbitrary distribution of the Brillouin frequency shift. In this early demonstration of the method, strain vibrations of a few hundred Hz are demonstrated, simultaneously measured on two different sections of an 85m long fiber, having different static Brillouin shifts and with a spatial resolution of 1.5m.

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OCIS codes: (060.2370) Fiber optics sensors; (290.5830) Brillouin scattering, (330.1880) detection; (190.0190) nonlinear optics.

References and links

1. Introduction

Fiber optic strain and temperature distributed sensors based on stimulated Brillouin scattering (SBS) have been extensively investigated in the last two decades. One of the more common approaches for implementing such a sensor, is the Brillouin optical time domain analysis (BOTDA). Here, a pump pulse wave, which is launched into one end of the sensing fiber, nonlinearly interacts with a counter propagating CW probe wave. This Brillouin-based interaction, which involves the excitation of an acoustic field, strongly depends on the optical frequency difference between the pump and probe waves, \( \nu_B = \frac{\Omega_B}{2\pi} \), which is around 11GHz for standard single mode fibers at 1550nm, with a narrow linewidth of ~30MHz. For a given fiber the exact value of the Brillouin Frequency Shift (BFS), \( \nu_B \), is sensitive to both the strain and temperature at the interaction position [1]. In the BOTDA technique the optical frequency of either the pump or source waves is swept across 100-200MHz to determine \( \nu_B \) along the sensing fiber, where the spatial resolution is determined by the pump pulse width. BOTDA systems have been commercialized and proved to be very efficient for long range distributed sensing. Classical BOTDA, however, has also its limitations. Due to the finite time required for the acoustic field to be excited by the interacting pump pulse and CW probe, the spatial resolution is limited to ~1m. Recently, several time domain techniques [2–4], as well as a correlation domain method (BOCDA) [5] have been developed, improving the spatial resolution down to the order of cm and mm, respectively. Measurement speed is also a concern with BOTDA: To achieve high strain/temperature resolution over a wide dynamic range of these two measurands, the scanned frequency range must be wide and of high granularity, resulting in a fairly slow procedure, which together with the need for averaging, limits the BOTDA method to the quasi static domain. Using a correlation domain technique, 200 Hz distributed sensing (at 1kHz sampling rate) was demonstrated at a single fiber location, with 10-cm spatial resolution and 20-m measurement range [6]. A variant of the correlation technique [7] achieved strain distribution along the entire length of a 100-m fiber with 80-cm spatial resolution and 20-Hz sampling rate. While impressive, it has been argued [8] that the number of spatially resolvable points for the correlation technique is limited to ~600, which is an order of magnitude smaller than the number achieved using pulse based techniques. Another attempt to perform dynamic Brillouin sensing [9] employs the dependence of the efficiency of SBS on the relative states of polarization of the pump and probe waves [10]. Thus, the application of stress to a fiber segment will change the polarization states of the two interacting waves, thereby affecting the strength of the Brillouin signal, although not in a way directly traceable to the magnitude of the applied strain. Still vibration frequencies of up to 5 kHz were demonstrated in a 1km fiber link [9]. Another approach [11] proposes to use multiple pumps and multiple probes to avoid the time consuming frequency sweeping required by the classical BOTDA technique. Measurement speed will potentially increase but at the expense of frequency granularity.

It turns out, though, that a small modification of the classical BOTDA setup can achieve very fast sensing, albeit with a limited dynamic range. Using the BOCDA technique and working at a fixed pump-probe frequency difference on the slope of the Brillouin gain spectrum (BGS), Hotate and Ong [12] have measured 50Hz vibrations at 2kHz sampling rate (single fiber location). More recently, by tuning the probe frequency to the center of the rising/falling slopes of the Brillouin gain spectrum (BGS), Romeo et al. [13] utilized the SBS interaction between two counter-propagating pump and probe pulses, meeting at a selected spatial location, to demonstrate fast strain-induced variations of the intensity of amplified probe wave with a sampling rate of 200Hz. The interrogated location was determined by the relative delay between the counter-propagating pulses. Clearly, at each interrogated location the optical frequency of the probe must be adjusted to properly sit at (or near) the center of the slope of the local BGS, whose peak is likely to vary along the sensing fiber according to the local average strain/temperature and/or fiber properties.
In this paper we propose a new method for fast and distributed Brillouin sensing, where the BFS of the optical fiber may vary arbitrarily along the fiber length. The method is based on the classical BOTDA technique, with the following modifications: instead of using a CW probe wave and a swept frequency pump pulse, it uses a pump pulse of a fixed optical frequency and a variable optical frequency CW probe wave. The time evolution of the probe frequency is designed in such a way that when the probe wave meets the counter-propagating pump pulse at location \( z \) along the fiber, the optical frequency difference between these two waves sits as close as possible to the middle of the slope of the BGS, as in [12]. Any fast change in the local strain or temperature will shift the BGS, and consequently, will be translated to gain variations of the probe wave. Using this technique the whole length of the fiber can be interrogated with a single pulse, or a few if averaging is required. Sec. 2 details the proposed method, first sketched in [14], while Sec. 3 describes the experimental setup and some results. We demonstrate the measurement of fast (400Hz) strain vibrations along 85m of a longitudinally Brillouin-inhomogeneous fiber, with a spatial resolution of 1.5m.

Fig. 1. An example of the Brillouin gain spectrum (BGS) distance-frequency distribution along a sensing fiber, having 3 different BGS sections with three different static \(-3\text{dB} \) frequency values, \( \overline{B}_{\text{dB}}(z) \), of 10.9, 10.95 and 10.85GHz, respectively, see inset.

2. Method

For an optical fiber in a real environment, the BFS, \( \nu_b \), as a function of both time and location along the fiber, can be described by:

\[
\nu_b(t, z) = \overline{\nu}_b(z) + \Delta \nu_b(t, z)
\]

where \( \overline{\nu}_b(z) \) and \( \Delta \nu_b(t, z) \), respectively, denote its static and dynamic components. By ‘static’ we mean a temporally slow enough change that can be easily monitored by classical BOTDA. Since this static (or averaged, in case of fast strain/temperature changes) BFS has a non-uniform spatial distribution along the fiber length, we first employ classical BOTDA (with a fixed pump frequency and swept probe frequency) to plot the static Brillouin Gain Spectrum (BGS), as a function of both the fiber length coordinate \( z \) and the frequency difference between the pump and probe waves. An example appears in Fig. 1, showing a fiber comprising three uniform sections, each with a different BFS. Searching for the \(-3\text{dB} \) contour along the fiber (say on the falling slope of the BGS), we deduce the range dependence of \( \overline{B}_{\text{dB}}(z) \), see inset in Fig. 2. Here, \( z = 0 \) is the point where the pump pulse enters the fiber, while \( z = L \) denotes the fiber end, which is also the entrance point for the probe wave. We then temporally tailor the frequency of the probe waveform so that when the pump pulse arrives at fiber location \( z \), it meets a probe wave, whose optical frequency is exactly...
below the pump frequency, ensuring Brillouin interaction around the $-3\text{dB}$ gain point of the BGS at location $z$.

To satisfy the requirements of the proposed method, we now consider a probe, having the following waveform:

$$E_{\text{Probe}}(t) = A_0 \exp \left\{ j[2\pi \nu_{\text{pump}} t - \phi(t)] \right\},$$

(2)

where $\nu_{\text{pump}}$ is the optical frequency of the pump, $\phi(t)$ is defined by

$$\phi(t) = 2\pi \int_0^t \nu_{B,3\text{dB}} \left( V_g t'/2 \right) dt',$$

(3)

and $V_g$ is the fiber group velocity. ($t = 0$ is chosen to be the time when the probe wave enters the fiber at $z = L$).

The propagation of the probe waveform through the fiber at $t \geq 0$ and $0 \leq z \leq L$ obeys:

$$E_{\text{Probe}}(t,z) = A_0 \exp \left\{ j[2\pi \nu_{\text{pump}} \cdot (t - [z - L]/V_g) - \phi(t - [z - L]/V_g)] \right\}, \quad t \geq [L - z]/V_g.$$

(4)

Therefore, the instantaneous frequency at $(t, z) | t \geq [L - z]/V_g$ is:

$$\nu_{\text{Probe}}(t, z) = \nu_{\text{pump}} - \frac{d\phi}{dt} = \nu_{\text{pump}} - \nu_{B,3\text{dB}} \left( V_g (t + [z - L]/V_g) / 2 \right)$$

$$= \nu_{\text{pump}} - \nu_{B,3\text{dB}} \left( [V_g t + z - L]/2 \right)$$

(5)

Thus, at $t = 0$ the probe enters the fiber at $z = L$ with $\nu_{\text{Probe}} = \nu_{\text{pump}} - \nu_{B,3\text{dB}}(0)$, and it is not until $t = L/V_g$ that the probe waveform arrives at $z = 0$, still having the frequency $\nu_{\text{Probe}} = \nu_{\text{pump}} - \nu_{B,3\text{dB}}(0)$. At that instant ($t = L/V_g$), a pump pulse, $E_{\text{pump}}(t) = A(t) \exp \left\{ j[2\pi \nu_{\text{pump}} t'] \right\}$

(6)

whose amplitude, $A(t)$, defined as centered at $t = 0$, is launched at the fiber entrance, $z = 0$. Its propagation through the fiber is governed by:

$$E_{\text{pump}}(t,z) = A(t - [z + L]/V_g) \exp \left\{ j[2\pi \nu_{\text{pump}} (t - [z + L]/V_g)] \right\}$$

(7)

An arbitrary fiber section at $z = z_0$, characterized by its own BFS, $\nu_{B,3\text{dB}}(z_0)$, is reached by the pump pulse at $t_0 = [z_0 + L]/V_g$. At these values of $t_0$ and $z_0$ the probe waveform has a frequency of (Eq. (5)):

$$\nu_{\text{Probe}}(t_0, z_0) = \nu_{\text{pump}} - \nu_{B,3\text{dB}} \left( [V_g (z_0 + L)/V_g + z_0 - L]/2 \right) = \nu_{\text{pump}} - \nu_{B,3\text{dB}}(z_0)$$

(8)

which is the probe frequency ensuring mid-slope gain for the probe.

Figure 2 describes the temporal evolution of the probe waveform tailored for the fiber of Fig. 1, as well as spatial snapshots of the probe and pump waves, counter-propagating through the fiber. Clearly, the waveform comprises 3 segments, each with its designed optical frequency. As dictated by the form of Eq. (5), each probe segment has twice the length of the corresponding fiber section.
Dynamic strain changes at \( z = z_0 \), spectrally shift the local BGS to lower or higher frequencies around its average value, \( \nu_{B,3dB}(z_0) \) (e.g., by \( 50\text{MHz}/1000\mu\text{s} \) for standard single mode fibers at 1550nm [15]). Thus, while meeting the pump pulse at \( z = z_0 \) and \( t = t_0 \), where \( t_0 = (z_0 + L)/V_g \), the probe at frequency \( \nu_{\text{Probe}} = \nu_{\text{Pump}} - \nu_{B,3dB}(z_0) \) will no longer experience the \(-3\text{dB} \) Brillouin gain; instead the gain will be lower or higher, depending on the direction of the BGS shift. Accordingly, the recorded probe intensity, arriving at the fiber edge (\( z = 0 \)) at \( t = (2z_0 + L)/V_g \) will reflect this gain change, which was induced by the strain at \( \{ t = t_0, z = z_0 \} \). The magnitude of the strain-to-gain conversion factor depends not only on the strain-to-frequency sensitivity but also on the slope of the previously measured Lorentian-shaped BGS. As mentioned above, this linewidth is around 30MHz for standard single mode fibers at 1550nm, provided the pump pulse width significantly exceeds the acoustic life time (~10ns). Unless special coding of the pump wave is employed [2,4], a shorter pump pulse gives rise to a broadened BGS, resulting in a more gradual slope.

Much like the classic BOTDA method, each pump pulse generates strain information from the entire fiber. Since there is no need to sweep the probe frequency, the sampling rate of the strain changes is limited only by the fiber length and the need for averaging to a value bounded by \( \left[ 2N_{\text{avg}} \frac{L}{V_g} \right]^{-1} \), where \( N_{\text{avg}} \) is the number of averages.

While this proposed technique enables a very fast true distributed sensing over a fiber with an arbitrary distribution of its static Brillouin shift, its dynamic range for dynamic strain measurements is limited. To ensure linearity of the strain-to-gain conversion, the dynamic...
strain variations to be measured must be constrained to generate frequency shifts (of the BGS) smaller than the frequency span of the linear part of the BGS slope (<30MHz for long pump pulses). Using the 50MHz/1000µS strain-to-frequency conversion factor, the resulting dynamic range is ~600μɛ [13]. Using short pump pulses to broaden the BGS [16] will benefit the dynamic range at the expense of smaller strain-to-gain conversion factor.

Finally, slow temporal variations of $\bar{\nu}_{B,\lambda_{dB}}(z)$ can be followed either by evaluating the average of the strain fluctuations coming from distance $z$, or by intermittent application of classical BOTDA. Using the updated value for $\bar{\nu}_{B,\lambda_{dB}}(z)$, the frequency composition of the probe waveform can be appropriately readjusted using Eqs. (2-3).


Fig. 4. The 85m FUT, comprising five sections of SMF fiber. The two 1m sections are mounted on manually stretching stages, making it possible to adjust their static Brillouin frequency shifts. Additionally, audio speakers are physically attached to these two sections in order to induce fast strain variations of various frequencies and magnitudes. All sections, with the exception of the two patch cords are made of the same fiber.

3. Experiment and results

A highly coherent 1550nm DFB laser diode (DFB-LD), with a linewidth of 10kHz, is split into pump and probe channels, Fig. 3. A complex waveform, to be described below, feeds the probe channel Mach-Zehnder modulator (EOM1), which is biased at its zero transmission point to generate two sidebands, the lower one for the probe wave and the upper one to be discarded later by the fiber Bragg grating (FBG) filter. The EOM1 output is then amplified by an Erbium doped fiber amplifier (EDFA1), optionally scrambled by a polarization scrambler (PS), and launched into one side of the fiber under test (FUT), Fig. 4, through the attenuator (ATT). Modulator EOM2 forms the pump pulse, which is then amplified by EDFA2 and...
launched into the other side of the FUT through a circulator (CIR1). The Brillouin-amplified probe wave is finally routed to a fast photodiode (PD) by CIR1 and CIR2. A narrow bandwidth fiber Bragg grating (FBG) filters out pump backscattering, as well as the upper sideband generated by EOM1. Finally, the output of the photodiode is sampled at 1GSamples/s by a real-time oscilloscope with deep memory.

Here \( \bar{\nu}_{B,3,db}(z) \) is a staircase function, representing the mid-slope frequency in each of the FUT sections. Since \( \bar{\nu}_{B,3,db}(z) \) is on the order of 11GHz, it is not easy to directly synthesize the probe waveform of Eqs. (2-3). Instead, a dual channel, 500MHz arbitrary waveform generator (AWG), together with a 0-20GHz microwave vector signal generator with I/Q inputs, are used to generate the RF input to EOM1. Thus, the signal generator frequency, \( f_c \), is set to a fixed value around, but below \( \min[\bar{\nu}_{B,3,db}(z)] \) (~11GHz), and we rewrite Eq. (3) as:

\[
\phi(t) = 2\pi \int_0^t \bar{\nu}_{B,3,db}(V_{s} t' / 2) dt' = 2\pi f_c t + 2\pi \int_0^t \left( \bar{\nu}_{B,3,db}(V_{s} t' / 2) - f_c t \right) dt' 
\]

and denote the second term on the right-hand side of (9) by \( \phi_{AWG}(t) \). Using this technique, the \( 2\pi f_c t \) term in (9) takes care of a fixed but high frequency component of \( \phi(t) \), while \( \phi_{AWG}(t) \) is responsible for the variable part of \( \bar{\nu}_{B,3,db}(z) \). Now the two channels of the AWG, \( V_i(t) \) and \( V_q(t) \) are programmed to output:

\[
V_i(t) = V_0 \cos[\phi_{AWG}(t)]; \quad V_q(t) = V_0 \sin[\phi_{AWG}(t)]
\]

These two signals of Eq. (10) are then connected to the I/Q inputs of the vector signal generator, whose output becomes:

\[
V_{RF}(t) = V_i(t) \cos(2\pi f_c t) - V_q(t) \sin(2\pi f_c t) = V_0 \cos(2\pi f_c t + \phi_{AWG}(t)) = V_0 \cos(\phi(t))
\]

\[
= V_0 \cos \left[ 2\pi \int_0^t \bar{\nu}_{B,3,db}(V_{s} t' / 2) dt' \right] 
\]

Biased at zero transmission, the EOM1 Mach-Zehnder modulator stops the pump frequency and using \( V_{RF}(t) \) of Eq. (11), generates a lower sideband of the form

\[
E_{Probe}(t) = E_{\text{EOM1}}(t) \propto \exp \left[ j \left( 2\pi \nu_{\text{pump}} t - 2\pi \int_0^t \bar{\nu}_{B,3,db}(V_{s} t' / 2) dt' \right) \right], 
\]

which is exactly the desired complex probe wave, as defined by Eqs. (2-3).

In all experiments reported below, 15ns wide pump pulses were used at a repetition rate of 625kHz. Once the pump pulse enters the 85m fiber, we need to collect data for 850ns (= 85m · V_s / 2) in order to monitor the full length of the fiber. Therefore, each pump pulse generates 850 (= 1GHz·850ns) recorded samples of the intensity of the Brillouin-amplified probe wave, as measured at \( z = 0 \). The sampled data were arranged in a matrix of \( N \) rows by \( M \) columns, where \( M = 850 \) is the number of oscilloscope samples per pump pulse, and \( N \) is the number of pump pulse cycles used in the measurement. To maximize the frequency resolution of the measured strain variations, data were continuously collected until the scope memory was effectively exhausted, resulting in \( N = 31,250 \) and a total recording time of 50ms (=N/625kHz), and, consequently, an expected frequency resolution of 20Hz. Thus, each column of the data matrix represents the time evolution of the strain at a particular location along the FUT, where the first and last columns, respectively report the gain at the beginning (\( z = 0 \)) and end (\( z = L \)) of the FUT.
We first demonstrate the distributed measurement of fast vibrations along fiber sections having the same BFS. For that purpose, the two 1m sections at the end of the 85m fiber, Fig. 4, were identically stretched, ensuring their Brillouin gain spectra overlap but away from the rest of the loose parts of the fiber. Here, EOM1 was simply fed by a single frequency RF sine signal, chosen to generate a probe wave, whose frequency coincided with the 3dB point of the common BGS. Using the audio speakers, the two sections were vibrated at different frequencies of 150Hz and 400Hz. Figure 5 presents the measured vibrations as a function of time along 10m out of the 85m FUT. Time sequences of two columns of the above mentioned measured data matrix, corresponding to the centers of the two 1m sections, also appear in the figure. Here gain readings were converted to frequency values using the measured slope of the BGS, as found from a classical BOTDA mapping of the FUT (shown below for the next experiment, Figs. 6-7), utilizing the same pump pulse and a swept CW probe wave. The obtained frequency variations can then be translated to strain values, and using the conversion factor of 50MHz/1000µε and the very little observed noise (0.25MHz rms, as measured at a location with no induced vibrations), quite high strain sensitivity is to be expected.

![Image](image_url)

**Fig. 5.** Top: Strain-induced gain vibrations at 150Hz and 400Hz were measured at the two 1m fiber sections, when adjusted to have the same BGS. Bottom: Time sequences from two columns of the measured data matrix, corresponding to the centers of the first and second sections, after 1kHz low pass filtering. Here gain variations were converted to frequency values. Note that each segment was excited by a different speaker and no effort was made to induce vibrations of the same magnitude in the two sections.

To demonstrate fast Brillouin sensing over a Brillouin non-uniform fiber, the two 1m sections, I and II of Fig. 4, were stretched to different strains, resulting in the Brillouin distance-frequency distribution of Figs. 6-7, as determined by a classical BOTDA measurement using the same 15ns pump pulse. Clearly, the Brillouin frequency shifts for sections I and II and for the 4m section between them are 10.9, 11.02, and 10.84GHz, respectively. Ignoring the non-vibrating 4m section, we chose to work on the falling slope of section I, $\tilde{\nu}_{B,3db}^{(I)}=10.93$GHz and on the rising slope of section II, $\tilde{\nu}_{B,3db}^{(II)}=10.99$GHz (Note that working on the negative slope results in signal inversion of the measured data).

In order to measure both sections with a single pump pulse, while ignoring the rest of the fiber, a composite probe waveform was synthesized, comprising a long segment, having an optical frequency falling outside the BGS of all sections of Fig. 6, followed by a 50ns segment, downshifted from the pump by 10.93GHz for section I, and another 50ns segment, downshifted by 10.99GHz for section II. The pump pulse and the probe waveform were temporally synchronized so that the center of the pump pulse meets the probe frequency...
change (from 10.93GHz to 10.99GHz) at the middle of the 4m section of Fig. 4. This synchronization ensures that in the absence of vibrations, the pump pulse, propagating in either section I or II, exclusively see the exact −3dB probe frequency of that section. Note that had we strictly followed the recipe of the method (section 2 above) for the 1m-4m-1m sections, the probe waveform would have had comprised of the following segments: 10ns(10.93GHz)-40ns(10.87GHz)-10ns(10.99GHz) (assuming we work on the falling slope of the BGS of the 4m section). Instead, in this first demonstration of the method, we opted to concentrate on the two 1m vibrating sections and ignore the 4m section, as well as all other loose sections. Still, for a theoretical zero-width pump pulse, this could be accomplished by a 30ns(10.93GHz)-30ns(10.99GHz) probe, which provides proper coverage for the 1m-4m-1m sections. However, to maximize the interaction of our finite-width, 15ns pump pulse (~20ns at its base) with the probe, we chose the longer 50ns (10.93GHz)-50ns (10.99GHz) probe segments.

Fig. 6. Classical BOTDA was employed to measure the static Brillouin gain spectrum (BGS) distance-frequency distribution along the FUT of Fig. 4 when sections I and II were non-uniformly stretched. A 15ns pump pulse was used against a CW probe wave, whose frequency was sequentially swept to cover the relevant frequency range.

Fig. 7. A blow-up of the sections of interest appears this 3D drawing, indicating that the FWHM of the BGS is of ~60MHz, which is due to the use of a relatively short pump pulse of 15ns.
Applying 180Hz to section I and 320Hz to section II, we obtained the results shown in Fig. 8, clearly confirming the feasibility of this new technique. The bump at the center of the 4m section (distance coordinate: 79m) is an artifact originating from the interaction of the pump pulse with the frequency transition of the probe wave from 10.93GHz to 10.99GHz that occurs exactly at that point, as dictated by our synchronization. This fast transition contains frequency components in the vicinity of the BGS of the 4m section, resulting in the observed bump, which, as expected, shows no vibrations. Luckily, in a real-world scenario, sharp transitions of the BGS are not expected, except where two different types of fiber are spliced together.

![Fig. 8. Top: Strain-induced gain vibrations at 180Hz and 320Hz were measured at the two 1m fiber sections, having different BGS. Bottom: Time sequences from two columns of the measured data matrix, corresponding to the centers of the first and second sections, after 1kHz low pass filtering. Here too, gain variations were converted to frequency values. Like in Fig. 5, the difference in magnitude between the 180Hz and 320Hz vibrations is due to different excitation conditions.](image)

4. Discussion and summary

In this paper we proposed and demonstrated a novel method for SBS-based high-frequency distributed strain measurement for a fiber whose Brillouin frequency shift varies along its length. Since no frequency sweeping of either the pump or the probe is required, the upper limit on the measurement speed is set by the pump pulse repetition rate, as determined by the fiber length and the number of required averages. Operating on the slope of the BGS [13], the dynamic range of the allowable vibrations is limited by the frequency extent of this slope (~30MHz for not-too-short pump pulses), and can be effectively enlarged by employing pump pulses shorter than the acoustic life time [4]. The probe waveform can be adaptively modified to follow slowly changing static strain/temperature conditions. The proposed method is fully compatible with modern techniques for the enhancement of spatial resolution [2–4]. Further research is underway to study the various characteristics of the technique, as well as its performance in real-world scenarios.

**Acknowledgements**

This research was supported in part by the Israel Science Foundation.