# Compressed Sensing with *a priori* Information for Reconstruction of Remotely Detected Microfluidic Devices

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**Introduction:** Microfluidic devices, when married with sensitive and specific chemical and biological sensors, promise unprecedented parallelism, portability, and efficiency. The most common assays for these devices involve optical detection, which, in the biological case, require exogenous chromophores and expose cells to potential toxicity. Magnetic resonance (MR), by contrast, is capable of directly quantifying the constituents of a complex mixture non-invasively. Additionally, MR makes it possible to probe dynamics of flow on time scales of microseconds. Applications of NMR microfluidics are limited by poor filling factor and magnetic susceptibility created by chip geometry. One solution is "remote detection", in which spatial and chemical information about the flow in microfluidic devices is encoded into the magnetic degrees of freedom (McDonnell, Han, Hilty, Pierce, & Pines, 2005). The flow then carries the information to a single optimized point detector, such as a microcoil, creating sensitivity improvements of 2-3 orders of magnitude (Granwehr & Seeley, 2006). The resulting improvement in temporal and spatial resolution makes microfluidic NMR practical and allows complete integration of spectroscopy, imaging, and velocimetry on one platform. The tradeoff for this wealth of information is additional indirect dimensions. While this added dimensionality necessarily requires extended acquisitions, it can be optimized with fast imaging sequences and schemes. We have exploited compressed sensing to allow for shorter acquisitions. This would generalize the technique and make it more applicable to a variety of biological model systems. Coupling the capabilities of microfluidic devices to the rich spectral information of NMR can provide a crucial tool for such applications as metabolomics, proteomics, and cellomics.

Previously, we have shown that full reconstruction of microfluidic chip geometry is possible with high degrees of subsampling. This is a result of the sparse nature of most microfluidic chips, where features of interest occupy only a small portion of the imaging volume. To build upon this approach, we propose a reconstruction that incorporates information about the chip geometry, allowing even further degrees of subsampling.

**Method:** The general remote detection pulse sequence is illustrated in figure 1. Information is encoded in a volume coil that contains the entire microfluidic chip. The encoding step consists of excitation, phase encoding, spin echo, and a storage pulse. The storage pulse projects the encoded information onto the longitudinal plane for transportation to the detection coil. Additionally, velocity encoding gradients can be used, but were omitted for the purposes of this study. The encoded spins then flow into a remote microcoil, where detection occurs stroboscopically.

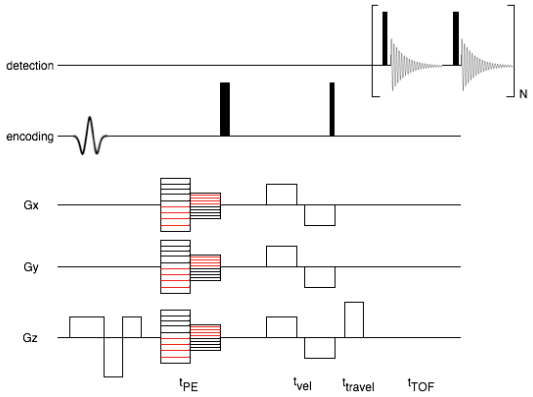


**Figure 1-Remote detection pulse sequence. RF encoding and detection is divided into two lines to indicate two spatially separated coils. Gradients are included for slice selection, phase encoding, and velocity encoding. The images for this study were not velocity encoded.**

A three dimensional image of a serpentine mixing chip was acquired using remote detection and 128 times sub-sampling. This degree of subsampling causes significant artifacts in conventional reconstruction. This includes cases where unsampled points are omitted or the subsampled acquisition is directly Fourier transformed. However, an accurate 3D reconstruction of the image can be achieved by accounting for the known gaps in the chip field of view. Within the compressed sensing algorithm, the $l_1$-norm of a sparse transform of the reconstruction was minimized and constrained such that the $l_2$-norm of the difference between the collected data and the reconstruction is negligible (Lustig, Donoho, & Pauly, 2007). Boundary constraints that incorporate *a priori* information about the chip geometry were imposed by manually selecting a mask from the conventional reconstruction. This constraint was used as additional data to fit with the sampled k-space points within the reconstruction algorithm. The masked points, known to have zero intensity, were added at a scaling factor to the sampled k-space points within a constraint vector. Reconstruction fidelity was dictated by the degree of scaling of the imposed mask.

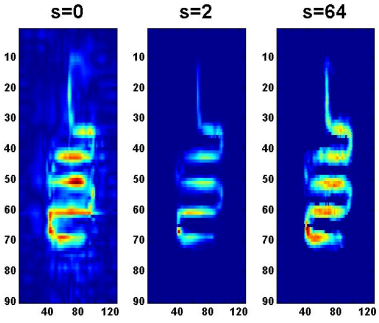


**Figure 2-Single slice of the serpentine mixing chip comparing increased mask scaling from left to right.**

**Results:** Figure 2 illustrates the effect of increased scaling (s) of the imposed boundary constraint on the image output. At very low s-values, the application of the imposed boundary constraint is limited. Specifically, the image at s=0 is indicative of a conventional sparse reconstruction based on sampling at the compressed k-space values. At high s-values, the boundary is overestimated and noise folds into the desired image space. An optimal reconstruction is achieved by choosing values between these extremes.

A full three dimensional reconstruction rendering is illustrated in figure 3, for s=2. This value was chosen as an optimization between unincorporated masking and over-constraining. The image resolution is 128 by 128 in-plane and 16 through-plane. Aspect ratios were set according to the corresponding field of view.

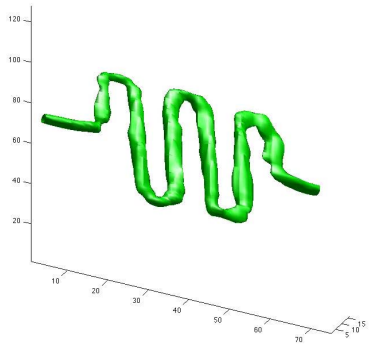

**Figure 3-Three dimensional reconstruction of chip geometry for a 128 times subsampled image.**

**Conclusions:** Microfluidic NMR has the potential of being a major analytical tool for the non-invasive investigation of a variety of biomedical model systems. It does, however, suffer from some drawbacks, including poor filling factor and magnetic susceptibility. These barriers are overcome with remote detection NMR, at the expense of long acquisition times. It is precisely in this sphere that specific applications of compressed sensing, such as the one demonstrated, will make this developing technique feasible. Additionally, this reconstruction technique could be extrapolated to a variety of MRI applications which have inherent sparsity, such as angiography, tumor localization, and 4D cardiac imaging.

**References**

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