Recent progress on wire-cell tomographic reconstruction for LArTPC

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Aiming for groundbreaking discoveries that can help unravel the mysteries of the origin and evolution of the matter by studying the neutrino oscillations and other phenomena.

1300 kilometers downstream, large far detector using LArTPC
Liquid Argon Time Projection Chamber

- Ionized electrons in LAr drift to sense wires [*drifting distance*]
- Three wire planes: two induction planes, one collection planes, different angles, *mm* wire pitch [*3 × 1D projection/view*]
- Photon sensor to record scintillation light [*start time*]
Event Reconstruction in LArTPC

- 3D reconstruction with excellent spatial resolution

- Challenges:
  - Tracks, showers, unknown vertex in LArTPC
  - Wire readout (intrinsic ambiguity)
    - Cold electronics power consumption in LAr and cost
    - Lose information of where the charge along the wire (pixel $n^2 \rightarrow 3 \cdot n$ wire), a pseudo-2D position + 1D time
Review of existing approaches

Signal Processing
(charge extraction)

2D pattern recognition
(Time + Wire) for each plane

Matching 2D patterns into 3D
Time, geometry, charge, etc.

汤图ology
(wire at a given time slice) ×
3 views/planes

2D imaging
Geometry, charge, connectivity, etc.

3D imaging
Time
+
3D pattern recognition

LineCluster, Pandora, PMA, DL, etc.

Each approach uses
the same information in different order/way.
Wire-cell Signal Processing

“Noise Characterization and Filtering in the MicroBooNE TPC”, MicroBooNE collaboration, accepted by JINST, on arXiv: 1705.07341

U plane, MicroBooNE event 41075, Run 3493

- Extract ionized charge from LArTPC (noise removal, 2D decon, ROI, etc)
- Basic for wire-cell event reconstruction
Wire-cell Tomographic reconstruction

LArTPC Signal Processing

minimum time unit

Create cells from wires

slicing

tiling

merging

3D image
(2D image + time)

3D pattern recognition

2D image

Practical cells for imaging

Imaging

3D pattern recognition

Simple

Charge

Truth

Simple

Wire-cell Tomographic reconstruction
Construct linear equation for imaging

- **Same charge in a voxel measured 3 times by wires on three planes**
- In practice, minimizing $\chi^2 = (B \cdot \vec{W} - G \cdot \vec{C})^T V^{-1} (B \cdot \vec{W} - G \cdot \vec{C})$
  - $W$: recon charge in single wire [signal processing], $B$: geometry matrix connecting single wire to merged wires [merging]
  - $C$: charge in merged cells [to be solved], $G$: geometry matrix connecting merged cells to merged wires [tilling]
- Easy to extend to wrapped wire case
Solving for imaging (1)

- Underdetermined linear equation
  - More unknowns (charge hits to be solved) than knowns (measured in wires) [intrinsic ambiguity of wire readout]
- Solutions can be found assuming/regarding sparse signal
  - LArTPC signal is typically sparse in space
  - Most of the charge hits are fake
  - Remove unknowns until solutions can be achieved and pick up the best one
- Issues
  - Combinatorial removal of unknowns, unrealistic number, NP-hard for computing

1) 5 knowns, 6 unknowns
2) Assuming one fake hit
3) 6 ways to remove one unknown
4) Pick up the best one, e.g. \( \chi^2 \)
Solving for imaging (2.0)

- Compressed sensing
  - a signal processing technique for efficiently reconstructing *sparse* signal, by finding solutions to *underdetermined linear systems*

- Important definition
  - $L_p$-norm of a vector $x$: $\|x\|_p = (\Sigma |x|^p)^{1/p}$
  - $L0$-norm is the number of non-zero elements of vector $x$
  - $L1$-norm is the sum of absolute value of elements of vector $x$
Solving for imaging (2.1)

• **L0-regularization problem**
  - Minimize L0-norm of vector $x$ [sparse], subject to $y = Ax$ [underdetermined]
  - Equivalent to minimize $\chi^2 = (y - Ax)^2 + \lambda \|x\|_0$
  - Solving linear equation of **wire-cell imaging** is a L0-regularization problem.

• **L1-regularization problem**
  - Minimize $\chi^2 = (y - Ax)^2 + \lambda \|x\|_1$
  - Well approximate (in most cases exactly recover) L0-regularization problem [apply to wire-cell imaging]
  - Irrelevant variables to exactly ZERO [sparse]
  - Convex, local minimum = global minimum [fast algorithms]
  - Regularization parameter $\lambda$ needs tuning according to data/MC, but has a non-sensitive region yielding similar/optimal results


A fast way to find the unique sparse solution using the so-called **L1-regularized minimization**
Solving for imaging (2.2)

- **Half a minute** (v.s. a few hours) to reconstruct the whole 3D image
- Matrix can be as large as $10K \times 1K$ (e.g., without merging)
- Space/time unit (precision) can be improved

Test of principle in wire-cell

[http://www.phy.bnl.gov/wire-cell/bee/set/d6323cd5-80e1-4721-9671-9c7c95c29e36/event/0/](http://www.phy.bnl.gov/wire-cell/bee/set/d6323cd5-80e1-4721-9671-9c7c95c29e36/event/0/)
Solving for imaging (3)

- Simple math description (basic $\chi^2$) considering time, geometry, charge, plus regularized term (sparsity) and additional penalty terms for other purposes, e.g. systematics, positivity

- A ‘best’ solution using the information we have and absolutely lose information to recover the ‘true’

- Use L0-regularization at present

- L1-regularization to solve the imaging problem
  - Breakthrough for wire-cell imaging
  - Implementation of L1-regularization in wire-cell near completion
Example of wire-cell 3D images

Simulation
DUNE 35t
2GeV $\pi^-$
wrapped wires

Truth

Wire-cell 3D image
(of charge)

http://www.phy.bnl.gov/wire-cell/bee/
Bee: interactive web-based 3D display (Chao Zhang, Brett Viren, etc.)
Wire-cell pattern recognition

- Very preliminary pattern recognition
  - Clustering based on 3D images of charge cells
  - Track and vertex identification
  - Shower identification (not finished)

Operations are all “local” i.e. Hough transformation, Crawler, Vertex fitting/merging ...

- Many topologies/corner cases
Summary

• Wire-cell **tomographic** event reconstruction for LArTPC is in good shape
  - Charge matching among wire planes demonstrated in uBooNE
  - Breakthrough of 3D imaging using L1-regularization
  - Use all the robust information (time, geometry, charge, sparsity, positivity, etc.) to do the imaging and evaluated by a single number $\chi^2$, a major step towards the automated reconstruction
  - Pattern recognition separated with 3D imaging, under rapid development

• Related tools/techniques
  - Wire-cell toolkit [https://github.com/WireCell/](https://github.com/WireCell/) (also include full TPC simulation, signal processing, etc.)
Backup
Illustration of L1-regularization


- Approximate L0
- Sparse

Best approximation of a point in $\mathbb{R}^2$ by a one-dimensional subspace using $l_p$ norms

- Approximate L0
- Convex (fast algorithm)

Norm evaluated along solution
Green: L1-norm

http://stemblab.github.io/intuitive-cs/