Melt Pool Monitoring Data Registration for Powder Bed Fusion Additive Manufacturing

National Institute of Standards and Technology (NIST)

Mentors: Dr. Yan Lu (NIST) and Dr. Zhuo Yang (NIST)

Judges: Dr. Brandon Lane (NIST), Dr. Hui Yang (PSU), Dr. Hyunwoong Ko (ASU)

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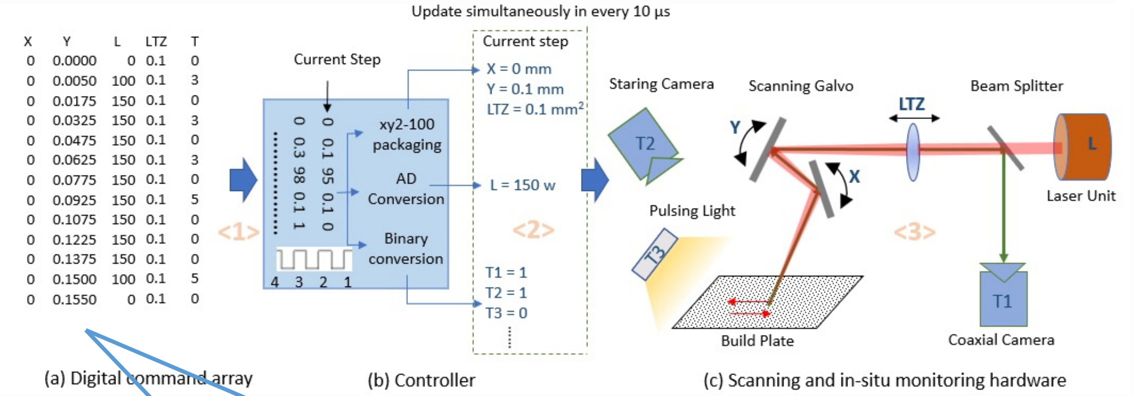
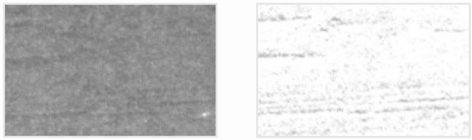
Background – AM and PBF

- Powder bed fusion process
- Fully control the laser scan path
- Advanced scan pattern
- In-situ monitoring data

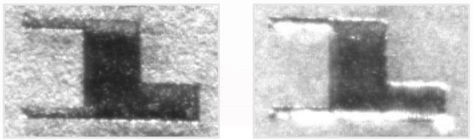


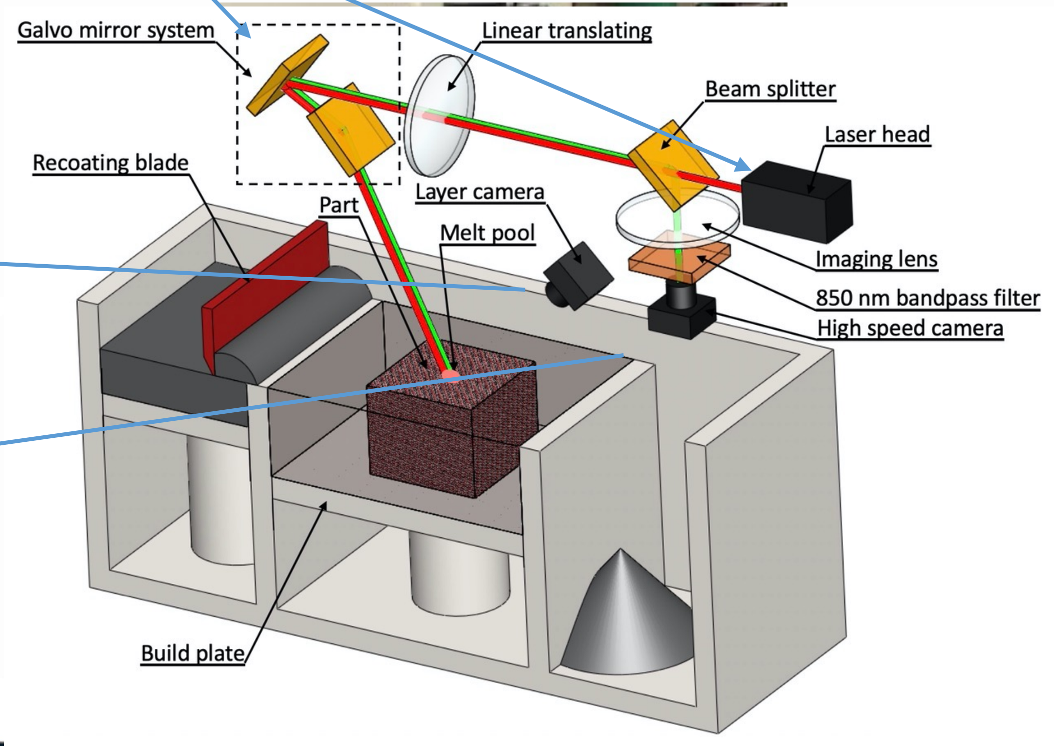
X	Y	L	LTZ	T
0	0.0000	0	0.1	0
0	0.0050	100	0.1	3
0	0.0175	150	0.1	0
0	0.0325	150	0.1	3
0	0.0475	150	0.1	0
0	0.0625	150	0.1	3
0	0.0775	150	0.1	0
0	0.0925	150	0.1	5
0	0.1075	150	0.1	0
0	0.1225	150	0.1	0
0	0.1375	150	0.1	0
0	0.1500	100	0.1	5
0	0.1550	0	0.1	0

Paved powder



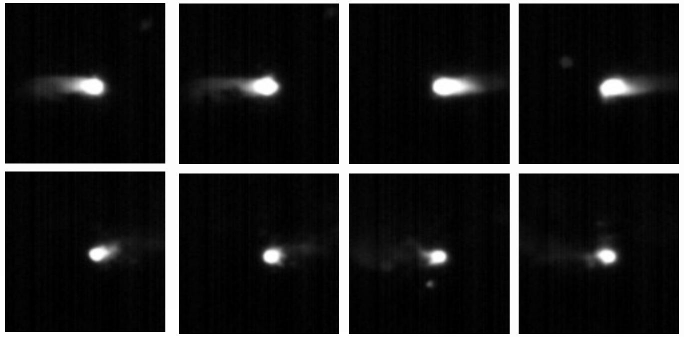
Burned layer





Regular

Irregular

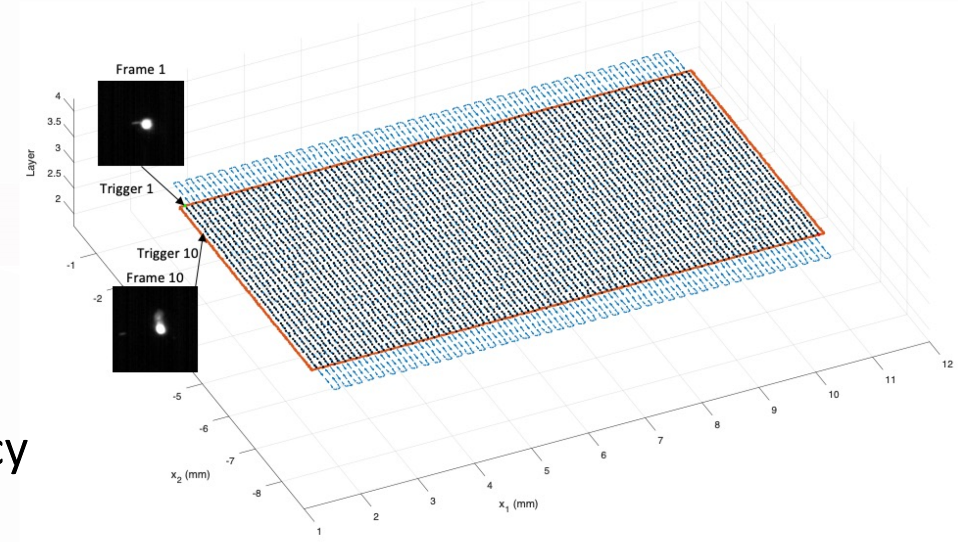


Challenges when dealing with all data together

- Data from different sensors and saved independently
  - Timestamp
  - Coordinate system
  - Format
  - …
- Without data alignment & synchronization, it is hard to
  - Analysis
  - Evaluation
  - Build model
  - …
- Solution – AM data registration

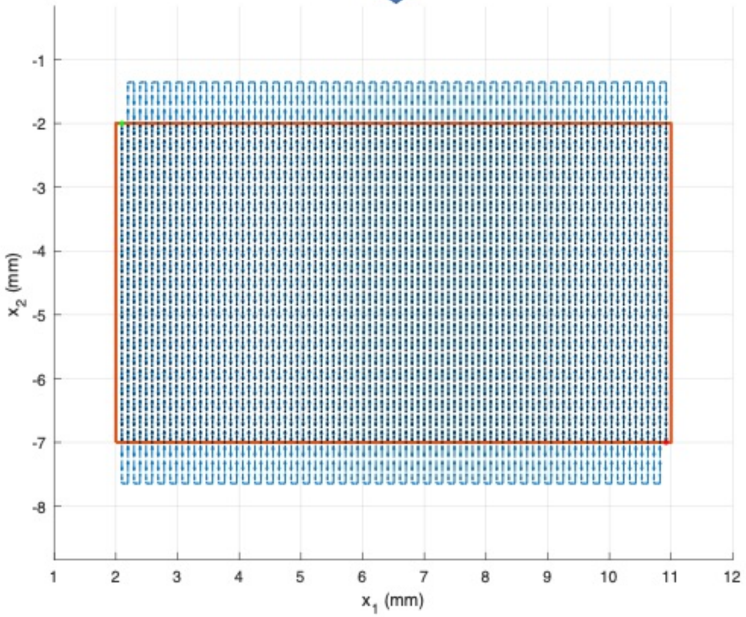
What is Image Data Registration?

- Alignment and synchronization
  - Laser positions were saved in command data
  - In-situ images were saved separately
- Challenges
  - Sensor delay
  - Missing data
- How?
  - In-situ image
    - File name
    - Feature
  - Scan strategy
    - Part shape
    - Pattern
    - Sample frequency
  - Command file
    - Camera trigger



Digital command

Step	x_1	x_2	Power	Trigger
1	0	0	0	2
2	0	0.008	100	0
3	0.005	0.016	195	2
...	...	...	...	...

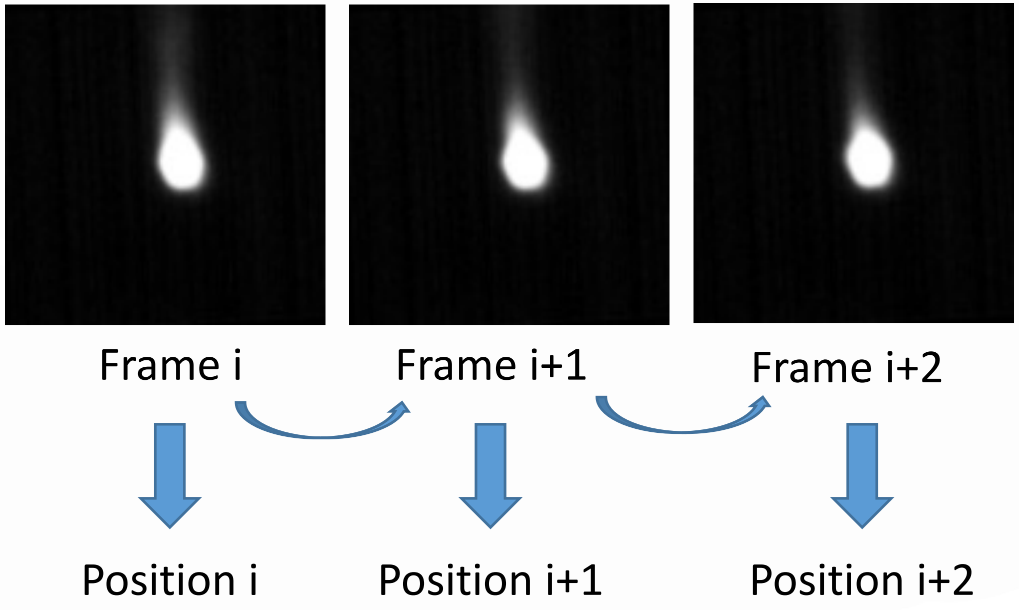


Designed position

Feng, Shaw C., Yan Lu, and Albert T. Jones. "Measured Data Alignments for Monitoring Metal Additive Manufacturing Processes Using Laser Powder Bed Fusion Methods." *ASME 2020 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers Digital Collection, 2020.

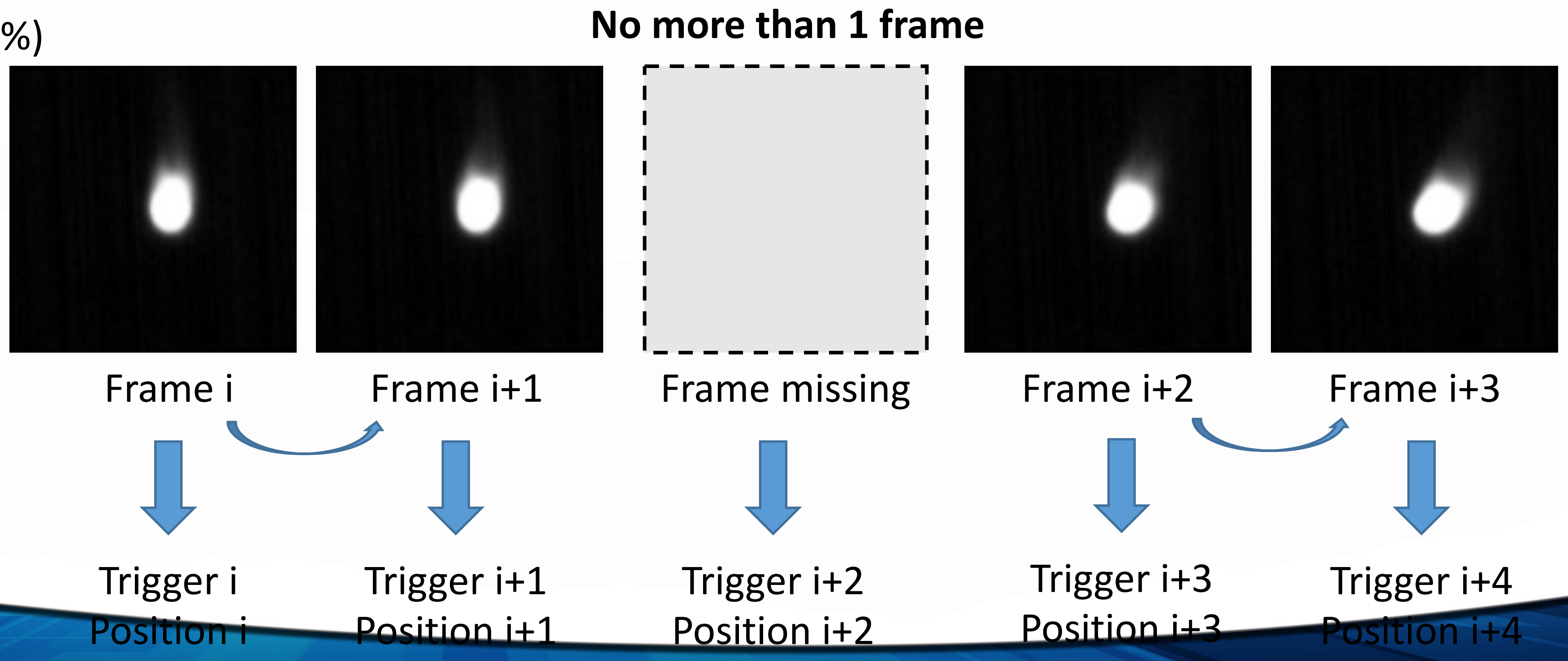
Part A – register ideal data

- Goal
  - Register the melt pool images to where they were taken in machine coordinate system
- Given information
  - Laser information at every step – position & power
  - Scan pattern – start point & sampling frequency
  - All images
- Features
  - No missing images
  - Constant frequency (10,000 fps – every 100 µs)
  - Regular scan pattern
  - Images only taken when laser is on
  - Start point == the first effective laser beam



Part B – register data with defect

- Same goal
- Given information
    - Laser information at every step – position & power & camera trigger (new)
    - Scan pattern – start point & sampling frequency
    - Image data
- Features
    - Few missing frames (< 3%)
    - Continues scan path



What to submit?

	A	B	C	D
1	frame#	time(¬µs)	x(mm)	y(mm)
2	1	0	0	0
3	2	0	0	0
4	3	0	0	0
5	4	0	0	0
6	5	0	0	0
7	6	0	0	0
8	7	0	0	0
9	8	0	0	0

Empty table

	A	B	C	D
1	frame#	time(µs)	x(mm)	y(mm)
2	1	0	-0.55973	4.3275
3	2	100	-0.569	4.2894
4	3	200	-0.569	4.2462
5	4	300	-0.569	4.1994
6	5	400	-0.569	4.1453
7	6	500	-0.569	4.0816
8	7	600	-0.569	4.009
9	8	700	[illegible]	[illegible]

Final table ready for submit (example)

- Register the data
- Fill in time/position for each frame

Evaluation

- Average error (Euclidean distance)

$$\varepsilon = \frac{\sum_{i=1}^{n} \sqrt{(x_i^a - x_i^r)^2 + (y_i^a - y_i^r)^2}}{n}$$

  - i: frame number
  - n: total frames
  - (x_i^a, y_i^a): actual position
  - (x_i^r, y_i^r): registered position
- Result worth 40% of final score
  - Part A – 20%, Part B – 20%

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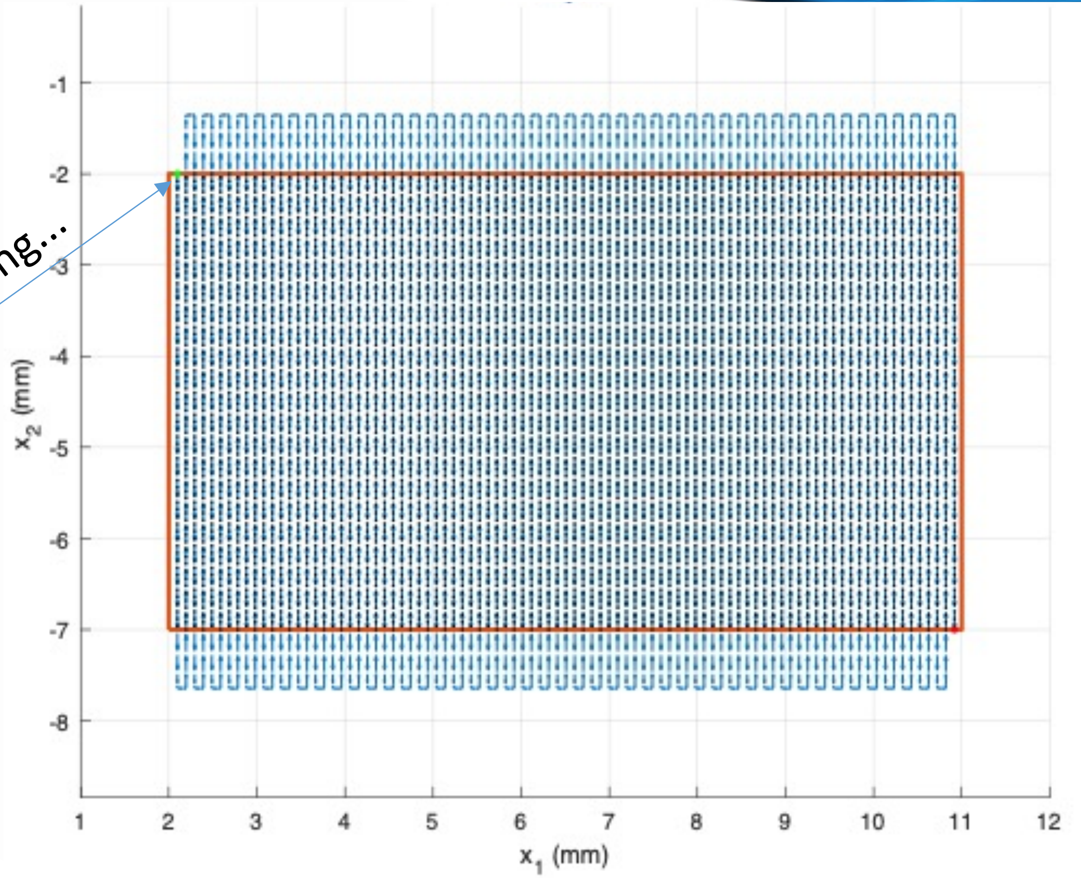
Example

1 time(μs)	2 x(mm)	3 y(mm)	4 power(w)
103390	2.1960	−7.1120	0
103400	2.1960	−7.1040	0
103410	2.1960	−7.0960	0
103420	2.1960	−7.0880	0
103430	2.1960	−7.0800	0
103440	2.1960	−7.0720	0
103450	2.1960	−7.0640	0
103460	2.1960	−7.0560	0
103470	2.1960	−7.0480	0
103480	2.1960	−7.0400	0
103490	2.1960	−7.0320	0
103500	2.1960	−7.0240	0
103510	2.1960	−7.0160	0
103520	2.1960	−7.0080	0
103530	2.1960	−7	195
103540	2.1960	−6.9920	195
103550	2.1960	−6.9840	195
103560	2.1960	−6.9760	195
103570	2.1960	−6.9680	195
103580	2.1960	−6.9600	195

Command file

frame000001?

Registering...



Plot

	A	B	C	D
1	frame#	time(¬μs)	x(mm)	y(mm)
2	1	103530	2.1960	-7
3	2	0	0	0
4	3	0	0	0
5	4	0	0	0
6	5	0	0	0
7	6	0	0	0
8	7	0	0	0
9	8	0	0	0

command_part_a.csv	Aug 8, 2021 at 23:23	1.7 MB
file_part_a.csv	Aug 8, 2021 at 23:23	39 KB
PA_MPM.zip	Aug 9, 2021 at 00:24	34.3 MB

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Presentation

- 10 – 15 minutes for presentation, 3-5 minutes Q&A
- Tell the judges the story in the next 24 hours…
  - Data
  - Features
  - Methodologies
  - Result
  - Findings
  - Problems
  - Visualization
  - …

Category	Criteria	Scoring
Technical Approach (30%) **Methods and algorithms**	• Requirement analysis and problem formulation • Literature review and exploration of ideas • The development and design of the idea • Scientific soundness of the approach • Creativity of the approach • Soundness of the algorithm (data pre-processing expected) • Readiness of the idea and the approach • Automated workflow: data/meta data acquisition through open interface	Excellent (9-10 pts) Very good (7-8 pts) Good (5-6 pts) Limited (3-4 pts) Poor (1-2 pts)
Results (40%) **Output performance**	• The objective is successfully achieved, with distance between the estimated position and the ground truth evaluated by the Root Mean Squared Error (RMSE) • Uncertainty analysis	Excellent (9-10 pts) Very good (7-8 pts) Good (5-6 pts) Limited (3-4 pts) Poor (1-2 pts)
Data Visualization (10%) **Clarity, information**	• Overall clarity of data presented • Visualization of data registration • Model development • Trend or correlation analysis	Excellent (9-10 pts) Very good (7-8 pts) Good (5-6 pts) Limited (3-4 pts) Poor (1-2 pts)
Overall Presentation (20%): **Organization, structure and message conveying**	• Title, headings, labels: Appropriate size, location, spelling, and content • The demonstration of teamwork • Structure and Clarity • Boarder impact of the idea to ME subfields	Excellent (9-10 pts) Very good (7-8 pts) Good (5-6 pts) Limited (3-4 pts) Poor (1-2 pts)

Good Luck!

Additional Slide – Part B Problem 3

For teams who choose Part B Problem 3 (NIST), I receive a good question and we want to clear a few points:

1. There is only one missing frame between two given frames (if there is). No consecutive frames can be missing between two given frames
2. We do have ground truth to evaluate your results.
3. You may want to try multiple features to guess the missing frames.
    1. The features could be any features of the image data
    2. Other features from the scan path may also help
4. The evaluation is based on the average registration error
    1. Other than pursuing the most accurate point-to-point registration, you may also want to choose a strategy that can minimize the average error
    2. Sometimes, mismatch one frame maybe even worse than mismatch two, why?
        1. If you mismatch one frame but following orders are 100% correct, all following frames (spatially) will always have one step offset
        2. If you mismatch one frame one step behind but a following frame one step forward, all following frames would have no offset
5. If you think the result must not 100% accurate, is there any way to minimize the registration error in visualization or further analysis?