# REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188



| 1. REPORT DATE (DD-MM-YYYY) | 2. REPORT TYPE | 3. DATES COVERED (From - To) |
|---|---|---|
| 11-03-2022 | Final Report | 5-Aug-2018 - 30-Dec-2021 |

4. TITLE AND SUBTITLE
Final Report: In situ 4D visualization

5a. CONTRACT NUMBER
W911NF-18-2-0192

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
73019-CS.6

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 15. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT | b. ABSTRACT | c. THIS PAGE | | | Lin Ma |
| UU | UU | UU | UU | | 19b. TELEPHONE NUMBER<br>434-924-3072 |

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

# RPPR Final Report
as of 14-Mar-2022

Agency Code: 21XD

Proposal Number: 73019CS **Agreement Number: W911NF-18-2-0192**

**INVESTIGATOR(S):**


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**Principal:** Y

Organization: **University of Virginia**
Address: The Rector and Visitors of the University of Virginia, Charlottesville, VA 229014195
Country: USA



DUNS Number: 065391526 EIN: 546001796
**Report Date:** 30-Mar-2022 Date Received: 11-Mar-2022
**Final Report** for Period Beginning 05-Aug-2018 and Ending 30-Dec-2021
**Title:** In situ 4D visualization
**Begin Performance Period:** 05-Aug-2018 **End Performance Period:** 30-Dec-2021
**Report Term:** 0-Other
Submitted By: Lin Ma Email: lm4wb@virginia.edu
Phone: (434) 924-3072
**Distribution Statement:** 1-Approved for public release; distribution is unlimited.


**STEM Degrees:** 1 **STEM Participants:**

**Major Goals:** This project proposes a collaborative effort between the University of Virginia, GVSC (U.S. Army CCDC Ground Vehicle Systems Center), and ARL (Aberdeen Proving Ground U.S. Army Research Laboratory) to investigate in situ visualization of 4D (all three spatial dimensions plus time) datasets. A 4-year project is proposed to accomplish three specific major goals. First, we propose to research algorithms and hardware that can rapidly pre-process large amount (on the order of tens of GB per second) of high dimensional data (3D and higher). To accomplish this goal, we propose to study the use of sparse representation, dynamics meshing, and also perform laboratory scale demonstration experiments. Second, we propose to research in situ visualization engine (VE), and our efforts will concentrate again on two specific directions: asynchronous rendering and super-spatiotemporal resolution. Third, we propose to test and demonstrate the algorithms and hardware developed above in collaboration with GVSC and ARL under the context of fire suppression, an ideal testbed to generate high dimensional data and an ideal application where in situ visualization is of critical importance for the Army.

**Accomplishments:** 1. Training of a PhD student (Chris Windle)
Since the project started in August 2018, the PI has recruited a new PhD student (Chris Windle), and has trained the student on the basics of four dimensional technologies, including the algorithms to perform 4D reconstructions, and also the experimental skills to obtain 4D measurements. The student has been maintaining excellent academic progress and successfully conducted both laboratory and field measurements described below. He has successfully passed his PhD qualification exam is preparing for his proposal defense and final defense.

2. Successful field demonstration at Aberdeen Proving Ground U.S. Army Research Laboratory (APG ARL)
In collaboration with ARL and GVSC, the PI and his PhD student completed a successfully field measurement campaign at APG ARL during Oct 2019. This field campaign demonstrated the implementation of the four dimensional sensor that we researched and developed in this project under field conditions in the vehicle test-bed at APG ARL. The sensor was demonstrated to overcome the anticipated challenges and enabled 4D measurements of simulated fire events in the vehicle test-bed. Combined with our 4D visualizing algorithms, 4D imaging data of fire events in the test bed were obtained at 500 Hz with a single camera, located at a safe distance outside the vehicle. The applicability of the sensor under field conditions and its capability to resolve the 4D dynamics (3D spatial structures plus temporal dynamics) open many interesting possibilities to further our fundamental understanding to substantially enhance vehicle fire safety. More details of the campaign and the result are provided in the PDF upload.

3. Dissemination
During the past reporting period, the research results have been disseminated through a total of three journal

publications, four conference publications, and one journal manuscript to be submitted. A detailed list of these publications is provided in the dissemination section.

**Training Opportunities:** The project primarily supported the training of a new PhD student, Chris Windle. Chris Windle's research has been supported by this project since Fall 2018. He has been the main person working with the PI to conduct the day-to-day research, the field measurement campaign, and the ongoing data processing and publication. He has been maintaining excellent academic progress and making steady progress toward his PhD defense. He has successfully passed his PhD qualification exam is preparing for his proposal defense and final defense.

**Results Dissemination:** The results have been extensively disseminated through professional conferences, peer-reviewed journals, the PI's daily educational activities and interactions with industry and national labs, et al. The following are examples of the dissemination efforts via conferences and journal publications during this project:

Journal Publications:
3D tomography reconstruction improved by integrating view registration
N Liu, Q Lei, Y Wu, L Ma, Applied optics 58 (10), 2596-2604, 2019.

3D Tomography Integrating View Registration and Its Application in Highly Turbulent Flames
Ning Liu, Ke Zhou, and Lin Ma, Combustion and Flame, in press, 2020.

In situ imaging of 4D fire events in a ground vehicle testbed using customized fiber-based endoscopes, Christopher I. Windle, James Anderson, James Boyd, Barrie Homan, Vamshi Korivi, Ma Lin, Combustion and Flame, Volume 224, February 2021, Pages 225-232

Conference Publications:
3D flame measurements using tomography reconstruction integrating view registration, N Liu, L Ma, AIAA Scitech 2020 Forum, paper 2208, Jan 2020, Orlando, FL.

Experimental demonstration of customized fiber-based endoscopes on a fire event within a military ground vehicle test-bed, Christopher I. Windle, James Anderson, James Boyd, Barrie Homan, Vamshi Korivi, Lin Ma, 2020 Spring Technical Meeting Central States Section of The Combustion Institute, May 17-19, 2020, Huntsville, Alabama.

Field demonstration of customized fiber-based endoscopes for 4D visualization of fire events in a ground vehicle test-bed, Christopher I Windle, James Anderson, James Boyd, Barrie Homan, Vamshi Korivi, Lin Ma, Submitted to 2021 SAE WCX conference, Detriot MI, Aug 2020.

Field demonstration of customized fiber-based endoscopes for 4D visualization of fire events in a ground vehicle test-bed, Christopher Windle, James Anderson, James Boyd, Barrie Homan, Vamshi Korivi, Lin Ma, 2021 JANNAF (Joint-Army-Navy-NASA-Air Force) meeting, December 2021.

Journal manuscript to be submitted:
Validation of an improved 3D flame tomography method by direct comparison to 2D PLIF measurements, Christopher I. Windle, Campbell D. Carter, Stephen D. Hammack, Lin Ma1, et al, to be submitted to Combustion and Flame , 2022.

**Honors and Awards:** Nothing to Report

**Protocol Activity Status:**

**Technology Transfer:** Nothing to Report

**PARTICIPANTS:**

**Participant Type:** PD/PI
**Participant:** Lin Ma
**Person Months Worked:** 2.00 **Funding Support:**
Project Contribution:

# RPPR Final Report
as of 14-Mar-2022

National Academy Member: N

**Participant Type:** Graduate Student (research assistant)
**Participant:** Chris Windle
**Person Months Worked:** 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

**ARTICLES:**

**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Applied optics
Publication Identifier Type: ISSN Publication Identifier: 2155-3165
Volume: 58 Issue: 10 First Page #: 2596
Date Submitted: 3/11/22 12:00AM Date Published: 4/1/19 12:00PM
Publication Location: United States
**Article Title:** 3D tomography reconstruction improved by integrating view registration
**Authors:** N Liu, Q Lei, Y Wu, L Ma
**Keywords:** 3D tomography, view registration
**Abstract:** Tomographic measurements involve two steps: view registration (VR) to determine the orientation of the projections and the subsequent tomography reconstruction. Therefore, the practical error in both steps impacts the overall accuracy of the final tomographic measurements. Past work treated these two steps separately. This work shows that the overall tomography accuracy can be enhanced substantially if these two steps are considered holistically because there is an opportunity for each step to leverage the information in the other step to improve the overall accuracy if they are considered holistically. Based on this recognition, this work has developed a new method called the reconstruction integration view registration (RIVR) method to implement such a holistic scheme.
**Distribution Statement:** 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Combustion and Flame
Publication Identifier Type: DOI Publication Identifier: https://doi.org/10.1016/j.combustflame.2020.
Volume: 221 Issue: First Page #: 429
Date Submitted: 3/11/22 12:00AM Date Published: 11/18/20 10:00AM
Publication Location:
**Article Title:** 3D tomography integrating view registration and its application in highly turbulent flames
**Authors:** Ning Liu, Ke Zhou, and Lin Ma
**Keywords:** 3D Tomography, Highly Turbulent Flames
**Abstract:** Recently, reconstruction integrating view registration (RIVR) has been demonstrated as an improved method to significantly enhance the accuracy of three-dimensional (3D) measurements in nonreactive flows. This work extended the RIVR method to 3D measurements of highly turbulent reactive flows with two specific goals. The first goal was to examine if the RIVR method can be effectively applied to highly turbulent flame structures, which display distinctively different spatial features from nonreactive flows. This examination of RIVR was performed specifically using two performance metrics, accuracy and spatial resolution. The second goal was to quantify the end benefits the RIVR can bring about on key flame properties involved in turbulence-chemistry interaction, such as flame surface density. The results demonstrated that the RIVR method can effectively enhance reconstruction accuracy of the thin flame front marked by CH radicals in 3D distribution. Compared to past methods, the RIVR me
**Distribution Statement:** 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

**Publication Type:** Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
**Journal:** Combustion and Flame
Publication Identifier Type: DOI Publication Identifier: https://doi.org/10.1016/j.combustflame.2020.
Volume: 224 Issue: First Page #: 225
Date Submitted: 3/11/22 12:00AM Date Published: 2/17/21 5:00AM
Publication Location:
**Article Title:** In situ imaging of 4D fire events in a ground vehicle testbed using customized fiber-based endoscopes
**Authors:** Christopher I. Windle, James Anderson, James Boyd, Barrie Homan, Vamshi Korivi, Ma Lin
**Keywords:** In situ imaging of 4D fire events, ground vehicle testbed
**Abstract:** Understanding the dynamics of fire events in ground vehicles is critical to improving crew survivability. To advance our understanding, four dimensional (4D) measurements are sorely needed to resolve both the temporal and spatial dynamics of fire events. However, there are several key challenges toward such measurements, including equipment requirements and optical access. 4D measurements, especially with sufficient temporal resolution, can be equipment intensive. Such equipment requirements are further compounded by the relatively hostile environments encountered in vehicular testbeds. Moreover, there is often very limited optical access available for obtaining such measurements within vehicular environments. This work describes the design and implementation of a customized fiber-based endoscope (FBE) setup to overcome these challenges in order to enable 4D flame measurements in a ground vehicle testbed located at the Army Research Laboratory, Aberdeen Proving Ground. Using a customiz
**Distribution Statement:** 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

**CONFERENCE PAPERS:**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 0-Other
**Conference Name:** AIAA Scitech 2020 Forum
Date Received: Conference Date: 06-Jan-2020 Date Published: 06-Jan-2020
Conference Location: Orlando, FL
**Paper Title:** 3D flame measurements using tomography reconstruction integrating view registration
**Authors:** N Liu, L Ma
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published
**Conference Name:** 2021 JANNAF (Joint-Army-Navy-NASA-Air Force) meeting
Date Received: Conference Date: 02-Dec-2021 Date Published: 02-Dec-2021
Conference Location: Virtual
**Paper Title:** Field demonstration of customized fiber-based endoscopes for 4D visualization of fire events in a ground vehicle test-bed
**Authors:** Christopher Windle, James Anderson, James Boyd, Barrie Homan, Vamshi Korivi, Lin Ma
Acknowledged Federal Support: **Y**

### Partners

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I certify that the information in the report is complete and accurate:
Signature: Lin Ma
Signature Date: 3/11/22 2:48PM

# Supporting Figures - Field Demonstration at Aberdeen Proving Ground Army Research Laboratory

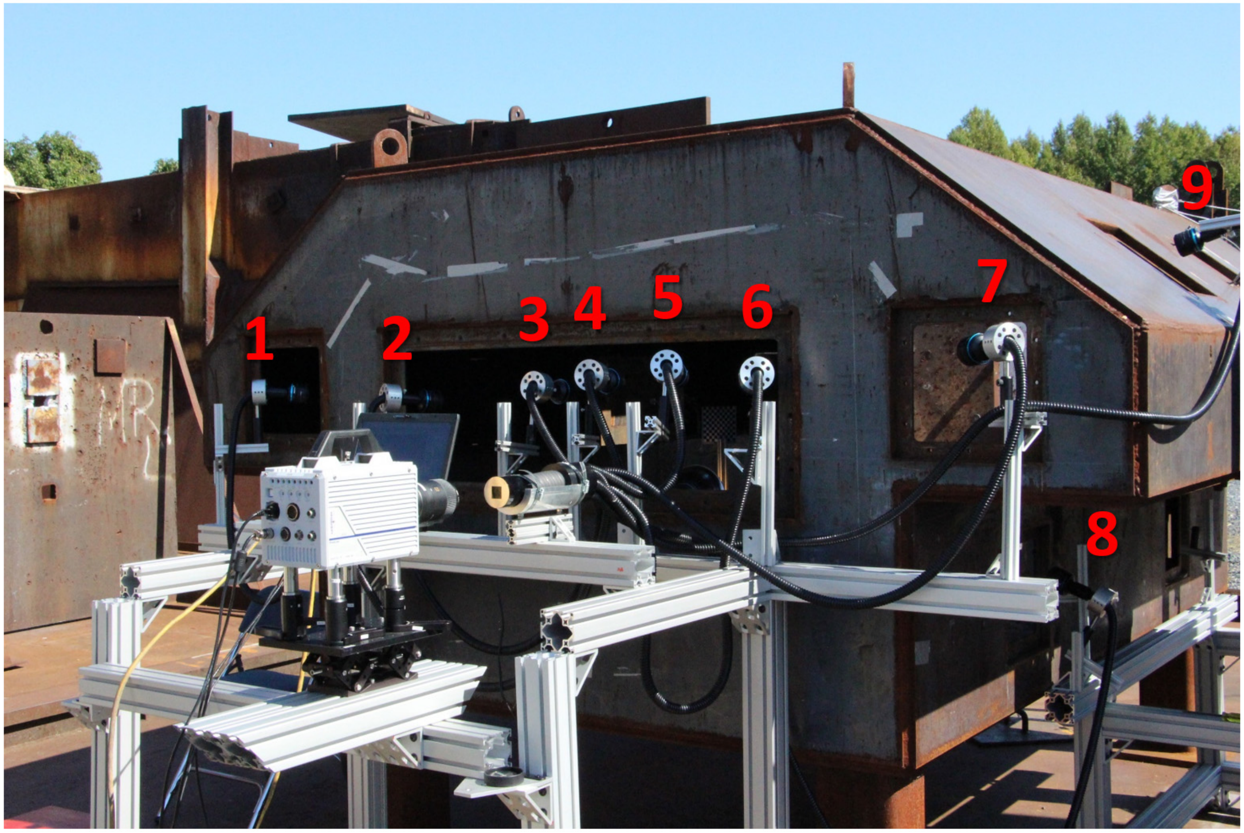


Figure 1: Setup of 9x1 customized fiber endoscope around the vehicle test-bed at the APG ARL.

Figure 2: Close-up of a pool fire event within the test-bed and two of the fiber endoscope inputs.

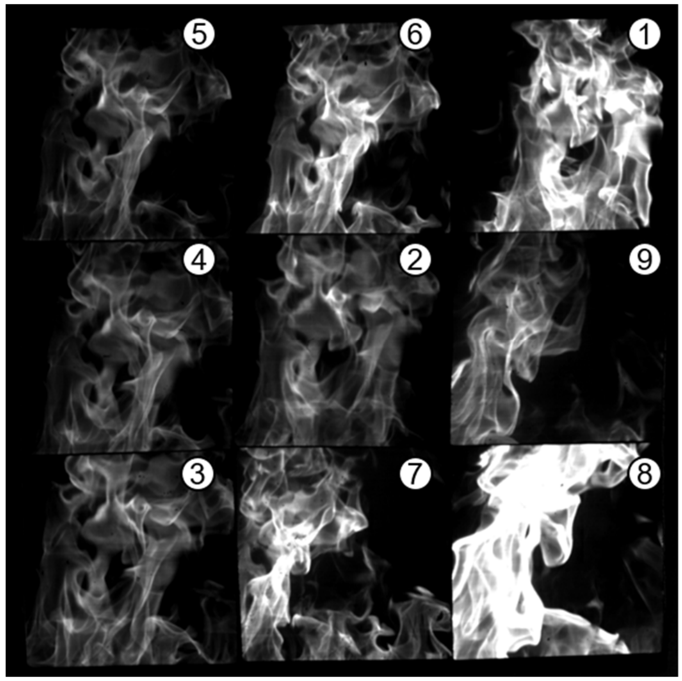


Figure 3: Example raw images captured by the fiber endoscopes from a total of 9 different orientations and a single high speed camera at 500 Hz.

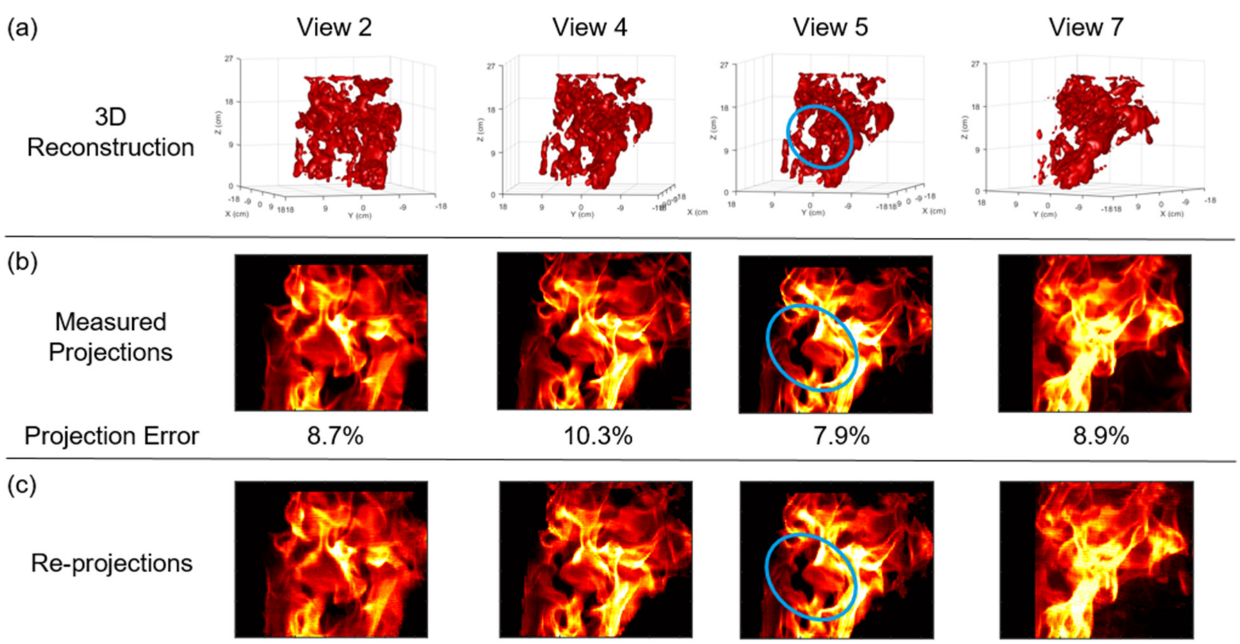


Figure 4: One example frame taken out of the 4D sequence: the resulting 4D reconstructions (a), the measured projections as well as the projection error between the measured projections and re-projections (b), and the re-projections (c) for views 2, 4, 5, and 7. The circled region in View 5 illustrates the large and small scale agreements.