CARNATIONS

Center for Assured & Resilient Navigation in Advanced Transportation Systems

ILLINOIS INSTITUTE OF TECHNOLOGY · CHICAGO STATE UNIVERSITY · UC RIVERSIDE · Stanford · VIRGINIA TECH

USDOT Tier 1 University Transportation Center
Semi-Annual Progress Report – No. 2

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Center Director:	Boris Pervan, Ph.D. | pervan@iit.edu | (630) 853-6689 Professor of Mechanical and Aerospace Engineering Illinois Institute of Technology
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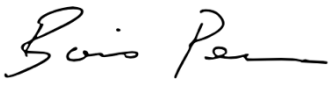
Signature:	

1 ACCOMPLISHMENTS

1.1. What are the major goals of the program?

The Center for Assured and Resilient Navigation in Advanced TransportatION Systems (CARNATIONS) is a Tier-1 University Transportation Center (UTC) created to address the USDOT's research priority area of *Reducing Transportation Cybersecurity Risks.* CARNATIONS is specifically focused on Resilient Positioning, Navigation, and Timing (R-PNT) and resilient vehicle-to-everything (V2X) PNT-relevant communications in multimodal transportation. The Center will benefit existing and emerging transportation systems by addressing PNT's evolving vulnerabilities. Our education and workforce development programs will support underserved communities. We will collaborate with stakeholders to develop demonstrable R-PNT performance metrics, rigorous standards, and open evaluation methods to enable seamless technology transfer.

1.1.1. Research

During this reporting period, CARNATIONS initiated nine comprehensive research projects, each led by experienced Principal Investigators (PIs), strategically aimed at advancing the frontiers of secure navigation and communication technologies. These projects and their respective PIs include:

No.	Ongoing Projects	University Partners	PIs	Status
1	GNSS Anti-Jam & Anti-Spoof Antenna Technology for Multimodal Transportation	Stanford, VT	Sherman Lo, Mark Psiaki	ACTIVE
2	Receiver Signal Processing to Resist GNSS Jamming and Spoofing Attacks	IIT	Boris Pervan, Samer Khanafseh	ACTIVE
3	Defending Against GNSS Jamming and Spoofing by Multi-Sensor Integration	IIT, UCR	Jay Farrell, Boris Pervan	ACTIVE
4	Radio-Frequency Signal Augmentation to Reduce PNT Jamming and Spoofing Risks	VT	Mathieu Joerger, Mark Psiaki	ACTIVE
5	Towards Resilient V2X Communications over 5G/6G Networks	VT, CSU	Walid Saad, Moussa Ayyash	ACTIVE
6	Multi-Vehicle/Infrastructure Jammer/Spoofer Detection and Localization	VT, UCR	Jay Farrell, Matthew Barth, Mathieu Joerger	ACTIVE
7	Threat Models and Use Cases for Multimodal Transportation	Stanford	Todd Walter, Sherman Lo, Sam Pullen	ACTIVE
8	R-PNT Virtual "War-Gaming" in a Multimodal Agent-based Simulation	VT	Hesham Rakha, Mark Psiaki	ACTIVE
9	Comprehensive Testing and Evaluation of Resilient PNT Systems	IIT, VT, UCR	Mathieu Joerger, Matthew Spenko, Matt Barth	ACTIVE

The PIs at CARNATIONS have pioneered research initiatives aimed at countering Global Navigation Satellite Systems (GNSS) jamming and spoofing and enhancing navigation system reliability. The PIs are instrumental in these efforts, underscoring the center's dedication to innovation and technological advancement in navigation and positioning technologies. have been contributing to nine research projects, which can be briefly described as follows below are the ongoing projects led by them:

(1) GNSS Anti-Jam & Anti-Spoof Antenna Technology for Multimodal Transportation

The project focuses on advancing multi-antenna detection and mitigation techniques for GNSS spoofing. This effort includes simulation-based and experimental studies aimed at enabling vehicles with single GNSS antenna systems to efficiently share tracking information and recover from spoofing incidents. The development of simulation models replicating RF front-end outputs from multiple receivers, along with ongoing experimental studies during actual spoofing events, play crucial roles in devising robust detection and recovery algorithms. Integrating dual-polarization antenna (DPA) technology with commercially available COTS patch antennas is also a key aspect. Commercially available equipment ensures compatibility with diverse transportation infrastructures. This project will enrich the development of effective countermeasure strategies against GNSS spoofing and interference through live engagements and global studies.

(2) Receiver Signal Processing to Resist GNSS Jamming and Spoofing Attacks

The project includes efforts focused on spoofing detection using advanced GNSS receiver signal processing techniques. Specifically, methods have been developed to detect spoofing by decomposing the GNSS Complex Cross Ambiguity Function (CCAF) into its true and spoofed components. While the challenge of determining which signals are spoofed and which are real has persisted, recent work has involved developing new methods using inertial sensors to specifically identify and exclude counterfeit GNSS signals.

(3) Defending Against GNSS Jamming and Spoofing by Multi-Sensor Integration

This research is focused on the integration of inertial sensors to detect spoofed GNSS signals, addressing quantifiable integrity risk. The PI’s and student’s recent findings have been consolidated into a journal paper accepted for publication in NAVIGATION. The paper details a method for detecting GNSS spoofing using INS, specifically targeting scenarios where a spoofer replicates authentic GNSS signals with only additive errors due to uncertainties in the spoofer’s knowledge of the target’s position. The team derives an optimal monitor to detect the anomalous temporal structure of spoofed measurements caused by the spoofer’s target tracking errors. The PIs have also submitted papers to the IEEE Transactions on Vehicular Technologies and to the IEEE Conference on Decision and Control and had one paper accepted at the American Control Conference. These three papers are on the topic of optimal measurement selection to minimize the risk of outlier inclusion subject to the constraint that the state estimate achieves a given level of accuracy. Recent contributions include reformulating the problem into a convex form, reformulating the constraint to

facilitate real-time computation, and defining methods to accommodate those scenarios where the constraint is not feasible.

(4) Radio-Frequency Signal Augmentation to Reduce PNT Jamming and Spoofing Risks

The goal of this research is to develop algorithms to enhance the resiliency of future navigation systems using GNSS and Low-Earth-Orbiting satellites (LEO). Preliminary performance evaluations show that resilient positioning through increased signal power, authentication, and frequency diversity is achievable worldwide, within a few minutes, using signals from GNSS and PNT-dedicated Xona satellites. The assumptions for this analysis were validated by CARNATIONS' industry partners at Xona Space Systems. Other initiatives include devising a plan to acquire S-band signals from LEO satellites and designing a prototype outdoor RFI-resilient transportation testbed at the Virginia Tech Transportation Institute (VTTI). These initiatives highlight the team's commitment to regulatory compliance and experimental validation.

(5) Towards Resilient V2X Communications over 5G/6G Networks

CARNATIONS PIs have been working in three crucial aspects of resilient communications and vehicular networks:

- Developing anti-jamming strategies for multiple-input, multiple-output orthogonal frequency-division multiplexing (MIMO-OFDM) wireless communications without prior assumptions about the adversary's setup. This innovative approach integrates information from wireless sensing services to counter-jamming signals. Optimization of beamforming, user scheduling, and power allocation in a multi-user MIMO-OFDM uplink scenario demonstrates robustness against various jamming scenarios, as confirmed by simulations.

- Designing a distributed solution for deploying large language models (LLMs) over realistic wireless networks. Leveraging split federated learning ensures resilience to wireless impairments and adversarial attacks. Solutions are sought that address challenges in beamforming, scheduling, and power allocation to maintain high task performance and model convergence, even in worst-case jamming situations.

- Investigating the resilience of vehicular platoons against cyberattacks targeting clock synchronization across the platoon. Rigorous analysis and modeling of clock synchronization errors define resilience metrics crucial for enhancing synchronization resilience. Fundamental analyses are carried out of various wireless impairments' impacts on platoon resilience and synchronization are also underway. These initiatives demonstrate significant progress in advancing network resilience and robustness in wireless vehicular environments, which is critical for future technological advancements and deployments.

(6) Multi-Vehicle/Infrastructure Jammer/Spoofer Detection and Localization

The PIs have been examining the impact of uncertainties on CAV applications, focusing on mobility, environmental, and safety factors. Notably, they are investigating scenarios such as platooning, which involve complex maneuvers like merging and splitting. Current research often deals with controlled environments mostly comprising connected and automated vehicles (CAVs), overlooking the diverse connectivity and autonomy levels within real-world traffic. The study emphasizes the need for sensitivity analyses considering model parameter uncertainties and sensor errors affecting CAV performance in mixed-traffic environments. The team aims to develop a simulation environment featuring diverse traffic agents with varied sensor capabilities. They plan to create a dynamic framework adjusting CAV parameters based on real-time sensor data, thereby evaluating application feasibility, cybersecurity risks, and operational anomalies.

(7) Threat Models and Use Cases for Multimodal Transportation

The PI team has been actively engaged in meetings related to this topic at the Radio Technical Commission for Aeronautics (RTCA) and Radio Technical Commission Maritime (RTCM). Specifically, the threats associated with this project are covered in Appendix W of the ED-259B standard. Recently, CMC Electronics has proposed a rescoping of this appendix, leading to the initiation of bi-weekly teleconferences focused on revising Appendix W. While there are no significant updates to report at this moment, it is worth noting that this area of study is gaining traction within the transportation community. There is growing urgency to enhance resilience against increasingly sophisticated spoofing threats, especially considering recent events in the Middle East and Ukraine.

(8) R-PNT Virtual “War-Gaming” in a Multimodal Agent-based Simulation

The team developed a cyber-attack scenario for the dynamic traffic routing ITS application. They modified the INTEGRATION traffic simulation software to model a cyber-attack on connected vehicles in the context of a dynamic traffic routing application. One of the challenges they faced was modeling the behavior of malicious vehicles and identifying the type of error/wrong information transmitted by malicious vehicles. The team is formulating techniques to detect and mitigate malicious information at the application level (dynamic routing application). One of the key findings is that there are different layers where cyber-attacks can be modeled (vehicles and/or ITS applications). The team’s next step is to run simulations to evaluate the impact of cyber-attacks on the performance of the communication and transportation systems in the context of the dynamic traffic routing application.

(9) Comprehensive Testing and Evaluation of Resilient PNT Systems

Currently, there are no flexible civilian facilities available to test resilient positioning, navigation, and timing (R-PNT) systems. The goal is to create new means for testing defense strategies against GNSS radio frequency interference (RFI). The first step involves designing an outdoor testbed at the Virginia Tech Transportation Institute (VTTI). It is situated in an isolated valley ideal for containing collateral RFI. The

strategy for responsible testing includes a layered RFI-minimization approach comprising directional antennas, emission power control, signal waveform designs, monitoring, and coordination with the FAA & FCC. CARNATIONS is actively engaging with VTTI and reaching out to the FCC and FAA. Additionally, the team is exploring alternative simulator-based testing with CARNATIONS industry partners at Spirent.

CARNATIONS Collaborative Endeavors

In addition to the research strides, CARNATIONS also conducted two technology assessments and completed reviews of twenty-two publications. Moreover, two students were offered internships as part of ongoing Skill Development Programs and Research Project Planning initiatives. These collective efforts of CARNATIONS PIs reflect significant progress in supporting and developing robust strategies for GNSS spoofing detection and mitigation, enhancing navigation system resilience, and establishing flexible testing methodologies for resilient PNT systems.

1.1.2. Leadership

In our ongoing dedication to excellence, CARNATIONS remains resolute in its mission to lead the global domain of R-PNT research, education, and workforce development. Our continuous efforts prioritize pioneering research initiatives and to establish and maintain the highest industry standards. Cultivating a vibrant educational environment nurtures the next generation of leaders capable of propelling innovation in resilient PNT technologies. These endeavors contribute significantly to advancing the resilience of global navigation systems and reinforce our position as a foremost authority in this crucial field, thereby shaping the future of navigation and positioning technologies.

Additionally, CARNATIONS proudly served as a sponsor for the IEEE-FISTS 2024 Conference. It was held in Riverside, California, from February 26 to 28, 2024. With a diverse audience comprising approximately 120 attendees from academia, industry, and government agencies worldwide, the conference focused on crucial topics such as eco-friendly transportation systems, advanced navigation techniques, electric vehicles, and sustainable freight solutions. Keynote speakers highlighted discussions on carbon-neutral mobility, while plenary sessions delved into topics like automated vehicles and AI-driven EV grids. CARNATIONS' sponsorship exemplified its dedication to advancing sustainable transportation and nurturing collaborative partnerships between industry and academia.

1.1.3. Education and Workforce Development

In the realm of education and workforce development, Moussa Ayyash, Co-Chair of the CARNATIONS Education and Workforce Development Subcommittee from Chicago State University, presented a comprehensive plan for the CARNATIONS Engineering Research Toolkit (ERT). This initiative aims to equip students and professionals with essential tools and resources for conducting advanced engineering subjects within the CARNATIONS framework.

The inaugural subcommittee meeting convened in February 2024, marking the commencement of collaborative efforts to devise an education plan tailored to students' needs. Subsequently, an Action Matrix tool was introduced in March 2024, streamlining the tracking of subcommittee progress and milestones within the center.

Under the guidance of Co-Chair Matthew Spenko, the Education and Workforce Subcommittee has actively spearheaded initiatives to enhance our educational outreach and industry collaborations. Key highlights include focused efforts on student outreach, fostering strategic industry collaborations, hosting impactful outreach events, and engaging alumni to contribute to the center's mission.

1.1.4. Technology Transfer and Collaboration

Significant progress has been made since October 2023 in Technology Transfer and Collaboration initiatives within CARNATIONS. Following the first Kick-off meeting in February 2024, guided by Co-Chairs Samer Khanafseh and Hesham Rakha, the Tech Transfer Subcommittee actively pursued partnerships with various organizations. The sub-committee outlined its strategic objectives, and a focused effort was made to enhance collaborations with related industries. This proactive approach led to notable success as three additional organizations Hexagon, QuNav, and Trimble aligned their interests with CARNATIONS.

In April 2024, an Action Matrix was introduced for the Tech Transfer Subcommittee, aiding the center in tracking progress and outcomes effectively. Through this tool, it was observed that the subcommittee worked specifically in advancing our technology transfer efforts, such as conducting a Patent Evaluation, fostering Industry Collaborations, organizing a Workshop, initiating an Internship Program for a student, engaging in an Alumni Engagement initiative, conducting a Technology Transfer Forum, developing Commercialization Strategies, and hosting two Outreach Events.

1.2. What was accomplished under these goals?

1.2.1 Research

Research Performance Metrics	Output
Number of new technologies, procedures/policies, and standards/design practices influenced by the research and adopted by organizations.	2
Number of internship opportunities provided.	1
Number of research articles presented in conferences and published in peer-reviewed journals.	14
Number of Articles and Papers Reviewed for study	15
Number of Student Outreach Initiatives	2

1.2.2 Leadership

Leadership Performance Metrics	Output
Number of keynote speeches/invited presentations at academic and professional conferences.	1
Number of leadership positions in local, national, and international organizations.	28
Number of CARNATIONS-affiliated students in scholar and professional leadership positions.	1

1.2.3 Education and Workforce Development

Education/Workforce Development Performance Metrics	Output
Student enrollment numbers and grades in CARNATIONS courses.	0
Number of participants logging in simulated “war-games.”	0
Number of collaborations with industry to gather knowledge about subjects	1
Number of Alumni Engagement to get support on Education and Workforce Development.	1
Number of Seminars.	1

1.2.4 Technology Transfer and Collaboration

Technology Transfer and Collaboration Performance Metrics	Output
Number of CARNATIONS research efforts successfully transferred to partners and stakeholders.	0
Number of new collaborative efforts between institutions formed because of CARNATIONS.	11
Number of CARNATIONS-affiliated Patents.	1
Number of CARNATIONS-related students joining partners or collaborators.	1
Number of CARNATIONS-related technology transfer forums.	1

1.3 How have the results been disseminated?

The results have been disseminated through various means. We presented multiple presentations at prestigious conferences such as the Institute of Navigation's ION GNSS+ 2023, the 2024 International Technical Meeting of the Institute of Navigation in January 2024, IEEE Global Communications Conference (GLOBECOM) 2024, and IEEE Transactions on Network Science and Engineering in January 2024. Additionally, they have been shared at the 2024 IEEE World Forum on Public Safety Technology and through journal papers such as "A Case Study in Downtown Chicago" in NAVIGATION and at ACC 2024 January 2024.

Presentations have also been made at events, such as ION Webinars (March 2024) and the AUVSI Ridge and Valley Chapter Symposium (October 2023). Various conference proceedings have included papers that amplified CARNATIONS' visibility and influence within the relevant disciplines.

Moreover, on March 22, 2024, IIT organized a poster competition in which students participated eagerly. It was a successful event, and the results were well-received and appreciated by a diverse audience, further contributing to the dissemination of findings, and fostering academic engagement. We are proud to report that CARNATIONS' sponsored PhD Student, Kana Nagai, won first prize in the PhD category.

1.3.1 What do you plan to do during the next reporting period to accomplish the goals?

In the coming reporting period, CARNATIONS will strategically pursue its research, education, and technology transfer objectives through meaningful initiatives. These include implementing the Engineering Research Toolkit (ERT) for synchronous R-PNT lectures and experiential learning across institutes. CARNATIONS also aims to engage 25-30 new companies for technology transfer and collaboration. Concurrently, we are preparing for our annual in-person meeting at IIT in July 2024 and scheduling three outreach events to engage stakeholders and the broader community.

We are also analyzing and closely monitoring the progress of ongoing research projects, particularly those that are set to conclude in September 2024. This involves assessing whether these projects require continuation or closure based on their outcomes and contributions. A detailed report on each ongoing research initiative is being prepared to guide our decisions on the necessary steps forward. Strengthening partnerships with existing collaborators remains paramount, and we actively seek opportunities for new collaborations to enhance our impact and bolster our research capabilities.

Furthermore, our Education Subcommittee is diligently working to meet industry demands for highly educated candidates. CARNATIONS plans to introduce new courses and requirements to enrich learning opportunities. Notably, IIT will commence teaching a new course in Fall 2024, MMAE 555: Introduction to Navigation Systems.

Additionally, the CARNATIONS' Education and Workforce Subcommittee will support IIT in extending these courses to students in other institutes, fostering collaboration and knowledge sharing beyond institutions.

2 PARTICIPANTS & COLLABORATING ORGANIZATIONS

2.1 What organizations have been involved as partners?

CARNATIONS has collaborated with several partners, including industrial organizations and esteemed universities. Our industrial partners include leading companies in various sectors, contributing expertise and resources to our research endeavors. Additionally, our partnerships with prestigious universities have enriched our academic

collaborations. This fosters innovation and knowledge in resilient positioning, navigation, and timing technologies. These partnerships are crucial in advancing our goals and ensuring the practical application of our research findings in real-world scenarios.

CARNATIONS University and industry partners are listed below.

Partner Institutes

No.	Institute	Principal Investigator
1	Illinois Tech	Boris Pervan, Samer Khanafseh, Matthew Spenko
2	Virginia Tech	Mathieu Joerger, Mark Psiaki, Hesham Rakha, Walid Saad
3	UC-Riverside	Jay Farrell, Matthew Barth
4	Chicago State	Mousa Ayyash
5	Stanford	Todd Walter, Sherman Lo, Sam Pullen

Industry Partners

No.	Industry	Person of Contact (POC)
1	TruNav	Samer Khanafesh
2	Hexagon	Sandy Kennedy
3	Trimble	David De Lorenzo
4	Spirent	Jeremy Bennington, Chris Coromelas
5	Satelles	Mike O'Conner
6	Xona Space Systems	Tyler Reid, Kurt Zimmerman
7	UrsaNav	Charles Schue
8	QuNAv	Andrey Soloviev

2.2 Have other collaborators or contacts been involved?

Yes, we have actively collaborated with a diverse array of partners and connections spanning industry and academia, significantly enhancing the depth and impact of our research initiatives while fostering enduring alliances. These collaborations have played a pivotal role in propelling forward our projects, guaranteeing their practical relevance and tangible outcomes. Our collaborative network comprises esteemed experts, organizations, and institutions committed to driving innovation in resilient positioning, navigation, and timing (PNT) technologies.

Noteworthy attendees at our CEC meetings, CAB subcommittee kick-off meeting, and all PI's meeting included representatives from the CARNATIONS Advisory Board, students, principal investigators (PIs), and external stakeholders, ensuring comprehensive engagement and strategic alignment across all facets of our research endeavors.

Education & Workforce Development Subcommittee Meeting			
No.	**NAME**	**ROLE**	**MODE**
1	Matthew Spenko	PI Co-Chair	Virtual
2	Steve Lewis	Member	Virtual
3	Charles Schue/Erik	Member	Virtual
4	Hadi Wasaf	Member	Virtual
5	Chris Hegarty	Member	Virtual
6	John Janeski	Member	Virtual
7	Boris Pervan	Director	In-person
8	Mathieu Joerger	Ass. Director	Virtual
9	Aashish Narang	Program Manager	In-Person

Research Subcommittee Meeting			
No.	**Name**	**Role**	**Mode**
1	Sherman Lo	PI Co-Chair	Virtual
2	Mark Psiaki	PI Co-Chair	Virtual
3	Charles Schue/Erik.J	Member	Virtual
4	Andrew Hansen	Member	Virtual
5	Chris Hegarty	Member	Virtual
6	John Raquet	Member	Virtual
7	Michael O'Connor	Member	Virtual
8	Steve Langel	Member	Virtual
9	Boris Pervan	Director	In-Person
10	Mathieu Joerger	Ass. Director	Virtual
11	Aashish Narang	Program Manager	In-Person

Technology Transfer Subcommittee Meeting			
No.	**NAME**	**ROLE**	**MODE**
1	Samer Khanafseh	PI Co-Chair	Virtual
2	Hesham Rakha	PI Co-Chair	Virtual
3	Charles Schue/Erik	CAB Chair	Virtual
4	Hadi Wasaf	Member	Virtual
5	Michael O'Connor	Member	Virtual
6	Tim Weisenberger	Member	Virtual
7	Boris Pervan	Director	In-Person

8	Mathieu Joerger	Ass. Director	Virtual
9	Aashish Narang	Program Manager	In-Person

ALL PI Meeting			
PRINCIPAL INVESTIGATORS			
No.	**Name**	**Role**	**Mode**
1	Boris Pervan	Director	In-Person
2	Mathieu Joerger	Ass. Director	In-Person
3	Aashish Narang	Program Manager	Virtual
4	Moussa Ayyash	PI	Virtual
5	Matthew Barth	PI	Virtual
6	Jay Farrell	PI	Virtual
7	Laura Freeman	PI	Virtual
8	Samer Khanafseh	PI	Virtual
9	Sherman Lo	PI	Virtual
10	Sam Pullen	PI	Virtual
11	Hesham Rakha	PI	Virtual
12	Walid Saad	PI	Virtual
13	Todd Walter	PI	Virtual
STUDENTS			
1	Lennon Headlee	Stanford	Virtual
2	Dawson Beatty	VT	Virtual
3	Birendra Kujur	IIT	Virtual
4	Kana Nagai	IIT	Virtual
5	Sahil Ahmed	IIT	Virtual
6	Wengxiang Zhao	IIT	Virtual
7	Christopher Harrison	IIT	Virtual
8	Mihir Nemana	IIT	Virtual

3 OUTPUTS

3.1 Publications, Conferences, and Presentations

Journal Papers

- Nagai K., Spenko M., Henderson R., Pervan, B., “Fault-Free Integrity and Continuity for Driverless Urban Vehicle Navigation with Multi-Sensor Integration: A Case Study in Downtown Chicago,” NAVIGATION, Vol. 71, No. 1, Spring 2024. Federal support acknowledged.

- Kujur, B., Khanafseh, S., and Pervan, B., “Optimal INS Monitor for GNSS Spoofer Tracking Error Detection,” NAVIGATION, Vol. 71, No. 1, Spring 2024. Federal support acknowledged.

Conference papers

- W. Hu, J.-B. Uwineza, J. A. Farrell, “Outlier Accommodation for Multi-GNSS Precise Point Positioning using Risk-Averse Performance-Specified Approach,” accepted to ACC 2024 in January 2024.
- Ahmed, S., Khanafseh, S., and Pervan, B., “GNSS Spoofing Detection and Exclusion by Decomposition of the Complex Cross Ambiguity Function with INS Aiding," Proceedings of ION GNSS+ 2023, Denver, CO, September 2023. Federal support acknowledged.
- Nagai, K., Ahmed, S., Pervan, B., “Integrity with LiDAR Incorrect Extraction Faults in Adverse Weather Conditions,” Proceedings of the 2024 International Technical Meeting of the Institute of Navigation, Long Beach, CA, January 2024. Federal support acknowledged.
- Andrei, V., Djuhera, A., X. Li, X., Monich, U., Boche, H., and Saad, W., “Resilient, Federated Large Language Models over Wireless Networks: Why the PHY Matters,” submitted to IEEE Global Communications Conference (GLOBECOM), 2024.

Presentations

- Nagai, K., ION Webinar, “Fault-Free Integrity of Urban Driverless Vehicle Navigation with Multi-Sensor Integration: A Case Study in Downtown Chicago,” April 3, 2024. Federal support acknowledged.
- Joerger, M., Jada, S., Yan, C. Psiaki, M., Bowman, J., “Resilient Positioning, Navigation and Timing for Safe Transportation,” AUVSI Ridge and Valley Chapter Symposium: Partnerships for Autonomy, Blacksburg, VA, October 2023. Federal support acknowledged.
- Saswat, P., “Infrastructure-assisted Cooperative State Estimation of Ego-Vehicle via Augmentation of Asynchronous Kinematic Measurements”, International Technical Meeting of the Institute of Navigation, Long Beach, CA, January 2024.
- Saswat, P., “Feasibility Studies on CAV Applications with State Uncertainties: A Survey,” IEEE FISTS 2024, February 2024.
- Zixi, L., “An Automated Pipeline for Detection and Localization of GNSS Interference sources,” Aerospace UPP Conference, April 2024.
- Anargyros, K., “Low-Cost GNSS Monitors for RFI Detection,” Aerospace UPP Conference, April 2024.

Submissions

- Hu, W., Mohsenian-Rad, H., and Farrell, J. A., “Optimization-Based Outlier Accommodation using Linear Performance Constraints for CAV State Estimation in Urban Environments,” submitted to IEEE T. on Vehicular Technology, March 1, 2024.

- W. Hu, Zeyi Jiang, Hamed Mohsenian-Rad, J. A. Farrell, “Convex Reformulation of Risk-Averse Linear State Estimation with Mixed-Binary Variables for Outlier Accommodation,” submitted to CDC 2024.

3.2 Website(s) or other Internet site(s)

In our commitment to maintaining an informative and engaging online presence, we diligently update our website, www.iitcarnations.org, every week following established guidelines. Our efforts align with current industry standards and best practices to ensure visitors receive up-to-date and relevant information regarding our research, events, and achievements. The analytics for our website reflect a significant outreach success, with a notable increase in daily traffic, showcasing a diverse audience engaging with our content regularly.

Furthermore, we are delighted to announce that our website newsletter has generated substantial interest, attracting over 50 new subscribers, and driving a substantial increase in website traffic (refer to Figure 1). This demonstrates a growing interest in our initiatives and underscores our dedication to fostering connections and sharing valuable insights with our community.

In February and March 2024, CARNATIONS successfully established its presence on LinkedIn, Instagram, and YouTube, marking significant strides in our digital outreach efforts. The analytics from these platforms indicate an impressive increase of approximately 944% in reach, reflecting growing engagement and interest in our center's activities (see Figure 2).

These platforms serve as valuable tools for expanding our outreach and connectivity programs, allowing us to engage with a diverse audience, including professionals, researchers, students, and industry stakeholders. Our LinkedIn page is a professional hub where we share insights and updates on research projects and industry collaborations. We aim to foster meaningful connections within the research and industry communities through engaging content and networking opportunities. The Instagram account provides a visual platform for showcasing our center's achievements, events, and initiatives, appealing to a younger demographic interested in technology and innovation.

Additionally, our YouTube channel offers a platform for sharing educational content, highlights from conferences, and webinars, enhancing our visibility and knowledge dissemination efforts. These digital platforms collectively contribute to our mission of promoting excellence and innovation in resilient positioning, navigation, and timing technologies.

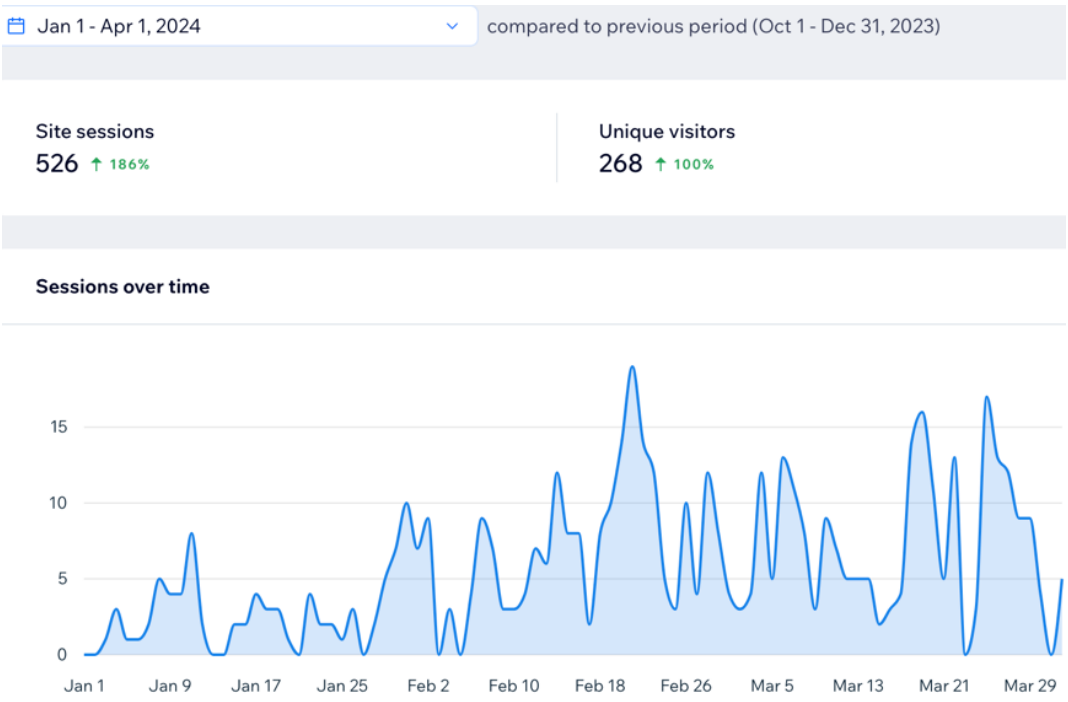


Figure 1: CARNATIONS' Website Traffic Overview

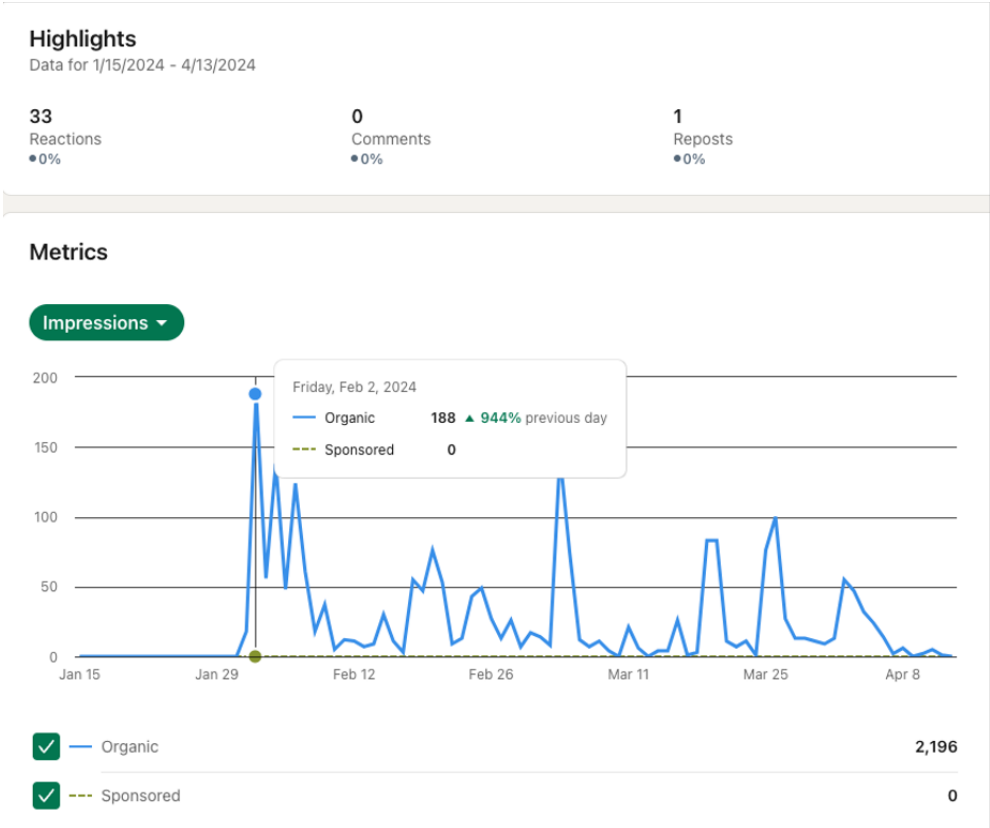


Figure 2: CARNATIONS' LinkedIn Analytics Output

3.3 Technologies or techniques

Nothing to report.

3.4 Inventions, patent applications, and/or licenses

CARNATIONS has initiated the patent application process for the innovative project titled "Optimal detector for GNSS spoofing using auxiliary sensors." The application is currently under review and processing at Illinois Tech, and we anticipate receiving approval shortly. This groundbreaking patent aims to address critical challenges in GNSS spoofing detection by leveraging auxiliary sensors to enhance detection accuracy and reliability. The pending approval underscores our commitment to advancing resilient positioning, navigation, and timing (PNT).

4 OUTCOMES

CARNATIONS achieved significant milestones across various strategic areas, reflecting our center's commitment to excellence and innovation in resilient positioning, navigation, and timing (PNT) technologies. One of our accomplishments included the successful initiation of nine research projects, including active participation and collaboration from all member institutions. These projects represent our dedication to advancing cutting-edge research and addressing critical challenges in modern navigation systems.

Our outreach efforts to industry partners yielded fruitful collaborations, with several new partners joining our network. This expansion reflected the industry's recognition of CARNATIONS' capabilities and expertise in developing impactful solutions.

The Education Subcommittee played an instrumental role in planning and implementing a new teaching strategy, aligning our educational programs with industry demands, and fostering the development of skilled professionals in the field.

CARNATIONS also made significant strides in knowledge dissemination and community engagement through various outreach events, including seminars, workshops, and student presentations. These events strengthened our ties with students, researchers, and industry experts.

In addition to our external engagements, internal initiatives such as the introduction of the Action Matrix tool. This enhanced our operational efficiency by effectively tracking and monitoring subcommittee activities. This structured approach ensured all tasks and objectives were met within established timelines and guidelines.

Furthermore, our sponsorship and participation in IEEE-FISTS 2024 highlighted our Center's commitment to promoting sustainable transportation systems and fostering industry-academic collaborations. We continued to foster a culture of innovation and collaboration, exemplified by the successful kickoff meetings for our subcommittees and the development of strategic course plans for upcoming educational endeavors.

Moving ahead, CARNATIONS remains focused on driving impactful research outcomes, expanding industry partnerships, and maintaining our position as a leader in resilient PNT technologies. These achievements underscore our dedication to advancing knowledge, fostering collaborations, and making meaningful contributions to the field and the broader community.

5 IMPACTS

5.1 What is the impact on the effectiveness of the transportation system?

Our inaugural CAB meeting provided insights into ongoing Resilient PNT challenges, leading to the creation of subcommittees with subsequent kick-off meetings. The engagement of separate co-chairs and active participation from all PIs facilitated robust strategic planning, ensuring comprehensive coverage of key research areas. This collaborative approach aligns our efforts with industry needs and research objectives, laying a solid foundation for future successes. Building upon this foundation, our first sub-committee kick-off meetings in February 2024 marked a significant milestone in refining our strategic direction and operational focus.

These engagements served as critical platforms to identify and address specific needs across various domains. Key priorities emerged, including a concerted effort to introduce innovative courses in our educational curriculum. Simultaneously, a targeted approach was delineated to foster closer collaboration with industry stakeholders, enhancing our tech transfer capabilities and impact. Furthermore, the structured evaluation process established for ongoing research projects approaching completion underscores our commitment to rigor and excellence in research outcomes.

These strategic insights from our collaborative endeavors shape a roadmap that ensures our efforts are finely attuned to industry needs and aligned with our research objectives. By leveraging these insights, we are solidifying our position as trailblazers in Resilient PNT technologies, driving transformative impact within our ecosystem and beyond.

5.2 What is the impact of technology transfer on industry and government entities, on the adoption of new practices, or on research outcomes that have led to initiating a start-up company?

The invaluable guidance provided by our tech transfer subcommittee and CAB members has directed our focus toward key strategic objectives:

- Encouraging the adoption of open standards within our research projects is paramount. Understanding the potential benefits and relevance of these standards to ongoing projects ensures alignment with industry practices and fosters interoperability across systems.
- Pursuing joint efforts for standardization, exemplified by harmonized threat models, strengthens our international collaboration efforts. By aligning perspectives from both the EU and US sides, we contribute to global

standardization efforts and promote cross-border cooperation in resilient PNT technologies.

- Integrating LEO/GNSS spoofing detection and mitigation techniques at the observable level through practical experiments is pivotal. Our focus on real-world demonstrations ensures robustness and reliability in addressing spoofing challenges, a critical step towards operational deployment.
- Advancing PNT technologies from offline testing to real-time prototype operations at TRL 6-7 signifies a significant future milestone. This transition validates the functionality and readiness of our technologies for practical applications, enhancing their market readiness and potential for widespread adoption.
- Collaborating closely with the Department of Transportation (DOT) and expanding industry partnerships accelerates the implementation of research outcomes. Demonstrating the effectiveness of our solutions in challenging conditions through red-team/blue-team operations solidifies confidence in our technologies among stakeholders and regulators.

5.3 What is the impact on the body of scientific knowledge?

The impact on the body of scientific knowledge from the CARNATIONS' papers during the period is extensive and diverse, contributing significantly across various domains:

- **GNSS Spoofing Detection and Exclusion by Decomposition of the Complex Cross Ambiguity Function with INS Aiding:** This work introduces a methodology for detecting and excluding spoofed Global Navigation Satellite System (GNSS) signals, integrating Complex Cross Ambiguity Function (CCAF) decomposition with inertial sensors, ensuring continuous navigation integrity even in challenging spoofing scenarios.
- **Integrity with LiDAR Incorrect Extraction Faults in Adverse Weather Conditions:** This paper addresses adverse weather impacts on LiDAR-based navigation for self-driving cars, ensuring accurate and safe navigation by mitigating incorrect feature extraction risks under varying weather conditions.
- **Fault-Free Integrity and Continuity for Driverless Urban Vehicle Navigation with Multi-Sensor Integration:** Investigating GNSS and inertial navigation integration with local landmarks, this paper ensures fault-free navigation for driverless vehicles in urban environments, bridging intermittent GNSS signal gaps for continuous navigation.
- **Optimal INS Monitor for GNSS Spoofer Tracking Error Detection:** Presenting a novel method for detecting GNSS spoofing using inertial navigation systems, this paper focuses on scenarios with challenging detection requirements, ensuring accurate and reliable navigation even in spoofing-prone environments.

- **Outlier Accommodation for Multi-GNSS Precise Point Positioning using Risk-Averse Performance-Specified Approach:** Addressing outlier issues in GNSS applications for precise positioning in Connected Automated Vehicles (CAV), this paper introduces a Risk-Averse Performance-Specified (RAPS) approach, improving accuracy and reliability, particularly in challenging real-world environments.
- **Resilient-by-Design Framework for Anti-Jamming in MIMO-OFDM Wireless Communications**: This paper introduces a resilient-by-design framework for effective anti-jamming in MIMO-OFDM wireless communications, integrating information from wireless sensing services to develop anti-jamming strategies without prior assumptions on the adversary's setup. The proposed approach demonstrates robustness against various jamming scenarios, contributing to enhanced security and resilience in future wireless networks.

These papers represent significant advancements in wireless communication optimization, navigation integrity, spoofing detection, outlier accommodation, and real-world application validation. They have significantly expanded our understanding and capabilities in these critical areas. In ongoing research within CARNATIONS, we anticipate presenting extensive new findings and developments in the upcoming months, contributing further to the scientific knowledge in these important domains.

5.4 What is the impact on transportation workforce development?

Guidance from the CAB Education and Workforce Development Subcommittee is crucial in driving our initiatives toward impactful outcomes and fostering long-term success in resilient positioning, navigation, and timing technologies. This collaborative effort is reflected in several key areas:

- **MS and PhD Programs:** We're focusing on offering specialized programs in Vehicle Navigation to develop a skilled workforce.
- **Internships and Employment:** Creating pathways for students to engage in internships and post-graduation employment opportunities, enhancing practical skills and industry connections.
- **Joint Workshops and Seminars:** Collaborative workshops and seminars with industry partners are planned to facilitate knowledge exchange and foster innovative solutions.
- **Industry-driven Capstone Projects:** Integrating industry challenges into capstone projects to provide hands-on experience and address real-world problems.
- **Diverse Course Offerings:** Expanding course offerings related to resilient positioning, navigation, and timing technologies to meet industry demands and student interests.

- **Enhanced Industry Collaboration:** Strengthening collaboration with additional industry partners to broaden our network, facilitate technology transfer, and support mutually beneficial research projects.

6 CHANGES/PROBLEMS

6.1 Changes in approach and reasons for change

Nothing to report.

6.2 Actual or anticipated problems or delays and actions or plans to resolve them.

Nothing to report.

6.3 Changes that have a significant impact on expenditures

Nothing to report.

6.4 Significant changes in use or care of human subjects, vertebrate animals, and/or biohazards

Nothing to report.

6.5 Change of primary performance site location from that originally proposed

Nothing to report.

7 SPECIAL REPORTING REQUIREMENTS

Nothing to Report