MIMO-PAD

Multiple-Input Multiple-Output Positioning for Autonomous Driving

Public report

Project within Traffic Safety and Automated Vehicles

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FFI Fordonsstrategisk Forskning och Innovation

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FFI in short

FFI, Strategic Vehicle Research and Innovation, is a joint program between the state and the automotive industry running since 2009. FFI promotes and finances research and innovation to sustainable road transport.

For more information: www.ffisweden.se

1. Summary

Connected and automated driving systems are predicated on having sensor data available to provide an understanding of the world, and to operate safely and reliably such systems need to combine information from multiple subsystems into a routine of detecting, estimating and taking appropriate action.

One bottleneck for all such systems today is the complete reliance on satellite navigation systems, the most well-known of which is GPS (the United States' Department of Defense's Global Positioning System). However, limitations of GPS-like systems include limited observability when sections of the sky are occluded, susceptibility to interference, and even malicious spoofing attacks, which has motivated a decades-long search for plausible alternatives.

Using wireless signals other than those broadcast by navigation satellites has been an alternative explored for decades, and has even enjoyed widespread commercial deployment in cellular systems as a fallback alternative offering positioning capabilities (with rather limited accuracy and precision) for emergency responders. In this project, the goal was to show that the "limited accuracy and precision" qualifier need not necessarily apply for signals from cellular systems. Even without depending on new generations of cellular technologies at ever-increasing frequencies and bandwidth, using the sorts of communication signals that have been commercially deployed for over a decade, with advancements in signal processing and a firm understanding of wireless channels, impressive performance can be achieved for such signals even in environments where satellite navigation always struggles. This was the aim of the MIMO-PAD (Multiple-Input Multiple-Output Positioning for Autonomous Driving) project. The team working in MIMO-PAD, primarily two industrial Ph.D. researchers enrolled at Lund University, demonstrated that this could be done using a novel demonstrator system built in the project.

The total budget was a large collective investment in knowledge building and technology development from the four participating partners, Volvo Cars, Terranet, Volvo Group and Lund University. In aggregate, the budget was 22,736,590 SEK, of which 11,322,950 was contributed by Vinnova through the FFI program. Results have been distributed through scientific conferences, journal articles, and a Ph.D. dissertation. The industrial and academic partners can build on this work as well as the scientific community at large.

2. Sammanfattning på svenska

Navigering för nästan alla tillämpningar idag är totalt beroende av satellitsystem, varav GPS är det mest välkända. Men satellitsignaler är ofta omätbara i miljöer där himlen inte är synlig, och signalerna även är känsliga för störning och vilseledning. Projektet MIMO-PAD (Multiple-Input Multiple-Output Positioning for Autonomous Driving) hade syfte att utveckla och demonstrera metoder för alternativ navigering, genom att passivt utnyttja befintliga signaler från kommersiella cellulära system och stödja applikationer som självkörande bilar som har höga krav på både noggrannhet och integritet. Projektet var ett gemensamt samarbete med tre industriella partners, Volvo Cars, Terranet, och Volvo Group, tillsammans med Lunds Tekniska Högskola (LTH). projektbudgten var 22.736.590 SEK, varav 11.322.950 försörjdes från Vinnova genom FFI programmet.

Alternativ navigering har varit ett stort område inom forskning de senaste åren, och detta projekt hade som sitt syfte att utnyttja cellulära signaler och uppnå bättre noggrannhet och precision än tidigare forskning genom att utnyttja kunskap om den trådlösa kanalen och avancerad signalbehandling. Denna noggrannhet skulle till och med visas i miljöer som är allra svåraste för traditionella metoder för trådlös positionering, tätbebyggda områden där signalerna reflekterar och breder ut sig på andra sätt som kan göra kopplingen med den fysiska geometrin besvärlig.

9 forskningsfrågor definierades och 4 arbetspaket togs fram. Några av forskningsfrågorna rörde det teoretiska om kanalmodellering och parametriska och icke-parametriska (maskininlärning) metoder för positionering. Andra examinerade praktisk implementering och ledde till konstruktion av ett unikt mätsystem för att kunna mäta kanaler med hög upplösning, även med cellulära systemets begränsade bandbredd. Några forskningsfrågor rörde integration med den tänkta tillämpningen av självkörande fordon, och den sista frågan involverade positionering med höga “millimetervåg” frekvenser. Detta millimetervåg system var ett mindre, mestadels självständigt arbetspaket som skulle baseras på en hårdvara/mjukvara plattform som köptes in i projektet, men strategin från partnern ändrade och projektet fick aldrig tillgång till hårdvaran. Tiden och resurserna omfördelades istället till andra arbetspaket.

Mätsystemet utvecklades och integrerades i en personbil och kördes genom centrala Lund för att observera signaler från kommersiella cellulära nätverk. Dessa signaler används båda för att karakterisera den trådlösa miljön, och även för att utveckla olika positioneringsmetoder. Det visade sig att lokalisering med maskininlärning visade väldigt lovande resultat utöver det som hade visats tidigare och den hög upplösningen av mätsystemet kunde utnyttjas utan att behöva beräkningskraft bortom det som är tillgängligt i fordon idag. Den parametriska lokaliseringen visade sig vara betydligt svårare, med den begränsade bandbredden och långa mättider för kanalen som flaskhalsar. Detta innebar att även om grundkonceptet visade sig fungera i den utmanande miljön, det inte fanns lika lätta vinster som med maskininlärningen.

Integrationen i själva tillämpningen utvecklades på en mer konceptuell nivå och ett antal publikationer (listan finns i kapitel 8.2 nedan) skrevs och blev publicerad i diverse vetenskapliga tidningar och konferenser. Publiceringarna rör allt från praktiska lösningar med det nya mätsystemet till lokaliseringsmodeller till en analys av funktionell säkerhet och en doktorsavhandling. Vissa av de övergripande programmålen för FFI och delprogrammet Trafiksäkerhet och Automiserade Fordon (TSAF), som analyserades i projektansökan, har adresserats och kan hittas nedan i kapitel 6.

Fortsatt arbete pågår delvis i samarbete med ett annat Vinnova projekt (B5GPOS) och delvis utvecklas nya metoder med data som samlades in i detta projekt. Navigering med alternativa trådlösa signaler har kommit in till den allmänna diskussionen ännu mer nu vid projektslut än från projektstart, och arbetet har lett till viktiga bidrag i området.

3. Background

A critical task for any driver is navigation. It is necessary to understand where one is in the world and on the road and plot a safe path to the destination that is continuously updated as a function of the dynamic traffic environment. For a human driver in familiar terrain, this might be a mental map of the road network. Automated navigation systems in phones or vehicles combine an electronic map with estimates of global position and orientation.

These estimates of global position and orientation today are derived almost entirely from global satellite navigation systems, and while the estimates may be fused with observations of relative movement, such as odometry from wheel encoders or cameras, the original estimate of world position and orientation is derived from satellites. For an autonomous system, this complete dependence is a challenge for ensuring continuous and safe operation.

Some applications employ alternative wireless signals for navigation, owing to the lack of satellite signal observability in obstructed environments. Cellular base stations and mobile users can perform a form of granular multilateration with cellular signals to provide first responders with a rough estimate of position. Ultrawideband signals or mmWave signals can also be used for multilateration/triangulation with a sufficiently dense network of nodes (the density required owing to the limited range) in surveyed positions. So-called “fingerprints” are also used, where basic signal information from known transmitters such as Wi-Fi access points is associated with a position in a site survey.

However, there are a few limitations with these methods that limit their usefulness for advanced applications such as autonomous driving. For satellite navigation, not only is it of limited utility in built-up environments where the sky view is obstructed such as in cities, but the open nature of the signal definitions also makes them subject to spectacular cybersecurity attacks by malicious actors, even those of limited sophistication. The alternatives, deploying dedicated infrastructure, tend towards either broad coverage with limited resolution (the emergency responder solution) or extremely limited coverage with high resolution (ultrawideband-style nodes or mmWave). For these reasons, this project aimed to demonstrate broad coverage with high position accuracy and precision. Using existing infrastructure, commercially deployed cellular base stations, broadcasting at frequencies that enable broad coverage, the MIMO-PAD project aimed to demonstrate levels of accuracy and precision not achieved previously, aiming particularly at environments that are both interesting for commercial operation (densely built-up environments) and those which are most challenging for established methods of triangulation and multilateration using simple signal observation models.

4. Purpose, research questions and method

The need for alternative navigation methods is well-understood and has inspired investment by governments and funding agencies for decades. No "silver bullet" alternative to satellite navigation has been achieved yet, and the broad consensus of the navigation community is that numerous methods will need to be developed for different applications and for different environments. This project had the specific goal of developing methods for navigation applicable to difficult, satellite navigation-challenged environments for applications of autonomy. This entails having a navigating agent with larger physical aperture and computational power available than small, battery-powered devices like phones do, agents which also have higher demands on performance in terms of accuracy and reliability than most consumer devices.

Work packages were defined, roughly corresponding to theoretical work, technology development, integration and demonstration, as well as a separate work package that aimed to perform a smaller-scale analysis of mmWave technology.

The work package on theoretical work (work package 1) concerned itself with research questions including:
RQ1: What are the statistical properties of the targeted wireless propagation environment?
RQ2: How well can multipath components, which are the target "anchors" used for localization, be resolved given bandwidth and antenna aperture limitations?
RQ3: What parametric positioning methods are appropriate for this environment and what sort of performance can be demonstrated?
RQ4: Which non-parametric (machine learning) methods are appropriate and what performance can be demonstrated?

The technology development work package entailed integrating the features into an existing high-definition map structure.
RQ5: Given the results of the theoretical exercises of RQ1-4, how can this be integrated into a practical high-definition map?

RQ6: What is the primary utility for the larger system in terms of fulfilling a defined functional safety concept and ensuring or expanding the operational design domain?

Integration and demonstration entailed solving more practical and immediate issues.
RQ7: What hardware and software is necessary to perform high resolution channel resolution for such signals?
RQ8: What methods are appropriate for solving issues of inter-cell interference for such systems?

Finally, the mmWave work package intended to address a subset of these research questions to allow for a comparison with a technology that has attracted significant interest in industry and academia.
RQ9: How can (RQ1, 2, 3, 7) be addressed for higher frequency signals using more mature, commercially available prototyping hardware?

5. Deliverables

A number of deliverables were defined that were intended to systematically address the research questions defined in the previous section.

These involved a combination of theoretical and practical work. Deliverables 1A-1C comprised the majority of the academic work, however, because a demonstrator of quite this sort had not been built before, practical aspects of the measurement system design were also published as novel scientific contributions.

Deliverable	Brief Description
1A	Multipath feature extraction in target environment
1B	Generic SLAM positioning framework
1C	Generic machine learning positioning framework
~~2~~	~~mmWave positioning framework~~
3	Layered positioning framework
4A	Vehicle-mounted demonstrator, sub-6 GHz
~~4B~~	~~mmWave benchtop demonstrator~~

The purchase of the mmWave system, for which budget and hours were originally allocated, was never completed owing to changing priorities from the project partner who had intended to lead the work. As a result, project resources which were intended to be allocated towards addressing these research questions and deliverables were re-allocated to other work packages. The mmWave related deliverables and results are therefore indicated with strikethrough text, and more exposition is offered in the following chapter.

6. Results

A mapping from the work packages, research questions to the deliverables and relevant publications (as well as cross-references within this report) is provided here, followed by a brief commentary on deviations from the original project application.

Research Questions (Chapter 4)	Deliverables (Chapter 5)	Publications (Chapter 8.2)
RQ1	1A, 4A	3, 5, 8
RQ2	1A, 1B, 4A	3, 4, 5, 6
RQ3	1B, 3, 4A	4, 5, 6
RQ4	1C, 4A	1, 2, 8, 9
RQ5	3	2, 7
RQ6	3	7
RQ7	1A, 4A	4, 5, 6
RQ8	4A	4, 5
RQ9	~~2, 4B~~	

As mentioned in the previous section, the mmWave system was never purchased, and while the generic methods and technologies from deliverables 1A-1C and 3 are largely applicable regardless of carrier frequency, the comparison was not completed to the extent hoped for with the original project application. To some extent, these research questions have been and continue to be addressed through collaboration with other Vinnova projects 5GPOS (Vinnova reference number 2019-03085) and the ongoing (as of the date of this report) project B5GPOS (Vinnova reference number 2022-01640). Those projects are dedicated to mmWave positioning, and have employed and built on several of the tools and methods developed in MIMO-PAD.

The level of software integration with Volvo Cars prototype vehicles for autonomous driving was also not as mature as the original ambitions outlined in Deliverable 3. This was in part because of the evolving relationship between Volvo Cars and the software company Zenuity/Zenseact, but also owing to the difficulty in arranging the physical meetings needed during the COVID-19 pandemic. Instead, a more theoretical approach was taken to this integration which is captured in part by publications 2 and 7. Further increasing the Technological Readiness Level of the project results would begin with a deeper integration along the lines of what was intended with Deliverable 3.

The vehicle-mounted demonstrator was intended to be mounted and deployed on not only a passenger vehicle, but also on a truck. However, Volvo Group needed to withdraw from the project around the midway point owing to changing priorities and allocations, which meant that the truck-deployed demonstrator did not come to fruition. Heavy vehicles are of interest to analyze not only because the different physical dimensions of the vehicle impact the propagation channel, but also because they tend to operate in varied environments where the reflectors and scatterers themselves are different than for typical passenger vehicle target environments, including in ports or mines.

7. Fulfilment of FFI program goals

In the initial project application, goals for both the FFI program at large and the Traffic Safety and Automated Vehicles sub-program specifically were identified and aligned with project goals. A retrospective regarding whether and the extent to which these goals were met is included in this chapter.

FFI Program Goal: increasing the Swedish capacity for research and innovation, thereby ensuring competitiveness and jobs in the field of vehicle industry

MIMO-PAD goal fulfilment: The project contributed to the development of two industrial Ph.D. researchers working in the vehicle industry, with one completed Ph.D. dissertation and forming the broad basis for the content of the second dissertation.

developing internationally interconnected and competitive research and innovation environments in Sweden

MIMO-PAD goal fulfilment: The world’s top-ranked navigation scholar according to ScholarGPS, Professor Zak Kassas (https://car.osu.edu/news/2024/08/kassas-named-top-navigation-scholar-world), travelled to Lund to serve as faculty opponent for the Ph.D. defence in the project and gave high acknowledgment on the dissertation, and his group has cited the publications (included below) numerous times in their continued work. This must be seen as a success for Swedish competitive R&D.

promoting cooperation between industry, universities and higher education institutions

MIMO-PAD goal fulfilment: The project was a collaboration of multiple companies working in the vehicle industry and Lund University. Three of the four partners were included in almost all the publications and the demonstration was a joint effort.

promoting the participation of small and medium-sized companies

MIMO-PAD goal fulfilment: Terranet as a medium-sized company was an active participant and a primary beneficiary of the project, sponsoring an industrial Ph.D. student and building knowledge in the area.

promoting cooperation between different OEMs

MIMO-PAD goal fulfilment: Volvo Cars was active throughout the project, but AB Volvo, which had a smaller role, was forced to withdraw after several years owing to staffing changes and shifting strategic priorities.

The FFI sub-program-specific goals identified were as follows:

Program Area A - Analysis, knowledge and enabling technology

MIMO-PAD goal fulfilment: Novel theoretical methods were developed for cellular localization, and demonstrated using a hardware and software platform designed within the project which showed performance beyond the state-of-the-art for the intended application and environment.

Program Area B – Foundational safety aspects of vehicles

MIMO-PAD goal fulfilment: The article "Cellular localization for autonomous driving: A function pull approach to safety-critical wireless localization" below offered a novel look at alternative navigation technologies and their place within an autonomous system designed for functional safety.

Program Area D - Intelligent and crash-avoiding systems and vehicles

MIMO-PAD goal fulfilment: Localization is an enabling technology for autonomy, which can contribute to a functional safety concept, but this work did not contribute directly to crash avoidance in the immediate manner that a new perception sensor would have.

Program Area F - Automated vehicles in the transport system

MIMO-PAD goal fulfilment: The work on functional safety and enabling localization in satellite navigation-challenged environments can contribute to commercial deployment of autonomous systems.

8. Dissemination and publications

8.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	The work was disseminated in scientific conferences in North America, Europe, and Asia, as well as at lectures for other partners. In the first years after publication the work has been cited by several leading research groups in the relevant areas.
Be passed on to other advanced technological development projects	X	The Vinnova B5GPOS project (ref: 2022-01640), among others, have built upon some of the work from this project.
Be passed on to product development projects		
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

8.2 Publications

Those publications from the project which have been accepted and printed are included here.

1. Whiton, Russ, Junshi Chen, and Fredrik Tufvesson. "Wiometrics: Comparative performance of artificial neural networks for wireless navigation." *IEEE Transactions on Vehicular Technology* (2024).

2. Whiton, Russ. *Dude, Where's My Car? Cellular Navigation for Autonomous Driving*. Ph.D. Dissertation, Lund University, 2024.

3. Whiton, Russ, Junshi Chen, and Fredrik Tufvesson. "Flexible Density-based Multipath Component Clustering Utilizing Ground Truth Pose." *2023 IEEE 98th Vehicular Technology Conference (VTC2023-Fall)*. IEEE, 2023.

4. Chen, Junshi, Russ Whiton, and Fredrik Tufvesson. "SLAM Using Cellular Multipath Component Delays and Angular Information with JPDA Approximation." *2023 8th International Conference on Signal and Image Processing (ICSIP)*. IEEE, 2023.

5. Chen, Junshi, et al. "High-resolution channel sounding and parameter estimation in multi-site cellular networks." *2023 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*. IEEE, 2023.

6. Chen, Junshi, Russ Whiton, and Fredrik Tufvesson. "Extended FastSLAM Using Cellular Multipath Component Delays and Angular Information." *2023 IEEE 97th Vehicular Technology Conference (VTC2023-Spring)*. IEEE, 2023.

7. Whiton, Russ. "Cellular localization for autonomous driving: A function pull approach to safety-critical wireless localization." *IEEE Vehicular Technology Magazine* 17.4 (2022): 28-37.

8. Whiton, Russ, Junshi Chen, and Fredrik Tufvesson. "LTE NLOS navigation and channel characterization." *Proceedings of the 35th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2022)*. 2022.

9. Whiton, Russ, et al. "Urban navigation with LTE using a large antenna array and machine learning." *2022 IEEE 95th Vehicular Technology Conference:(VTC2022-Spring)*. IEEE, 2022.

9. Conclusions and future research

In total, the MIMO-PAD project spanned just over five years, involved three Swedish industrial partners and Lund University, and was the primary financing mechanism for the large body of dissertation work of two industrial Ph.D. students. The results have informed continued research in the area of alternative wireless navigation in other research projects in Sweden and has been recognized by research groups outside of Sweden. A few of the important conclusions from the project are summarized here, together with an indication of work that will continue even now after the project has been finalized and suggestions for continued research beyond that.

One of the primary lessons of the project was that for the target environment of sub-6 GHz in an urban landscape, the complexity of doing parametric positioning with signals of limited bandwidth (the work of deliverable 1B) is quite possible but still extremely challenging, even with a large receiver aperture and significant computational power. The work on parametric positioning is still ongoing as the project draws to a close and the publication list below is not complete for the eventual outputs of MIMO-PAD.

By way of contrast with parametric positioning, machine learning at these frequencies was comparatively straightforward to implement (once the hard work of building the demonstrator was complete) and showed results well beyond what had previously been demonstrated for any comparable scenarios in literature with minimal run-time processing. Given that machine learning with one or a pair of base stations was so promising, an obvious route for future work is to look into effective ways of combining additional transmitter information for even more accurate and robust position estimates. The literature on machine learning and safety-critical machine learning expanded dramatically over the course of this project and there are innovations that should be easy wins for developing the promising results from MIMO-PAD even further, both by employing more modern architectures and by adding different types of transmitters as inputs.

On the subject of the demonstrator, the measurement system was implemented with a single receive chain and time-domain switching among the antennas, which is standard practice in channel modelling but showed itself to be a rather irritating limitation when operating at the limited switching speed of sequential reference symbols broadcast by a commercial base station. This imposed strong limitations in vehicle's velocity that were cumbersome for data collection, lest the channel coherence time be exceeded. Future work should certainly aim to employ parallel sampling among antennas to avoid these limitations to make testing on larger geographical scales more feasible as well as to make fusion with other sensors (inertial units and wheel odometry) more meaningful when the merits of a system like this is to be compared with other types of sensors.

With the advent of new generations of cellular communication, signal bandwidth and the number of antennas are continually increasing, and the concept of using coherent phase information from multiple transmitters and receivers is becoming more tractible. New frequency bands that can strike a better balance between coverage and bandwidth are also being introduced. Together with these developments, the principles and methods developed in this project can be applied in the future for better positioning performance.

Finally, future work should also address aspects of industrialization including packaging, scalability, robustness, business models, and functional safety. With the recent dramatic increase in the incidence of jamming and spoofing of satellite navigation systems, positioning with signals other than those of dedicated satellite navigation systems is more firmly in the public spotlight at the end of the project than it was in the beginning.

10. Participating parties and contact persons

Institution	Name	Contact	Logo
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