PROJECT NO: 3-023

Frictionless Ticketing for Public Transport

Appendix 4: Literature overview

JULY 2022

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Appendix 4 Literature Overview

Several technology options are available to deliver frictionless ticketing. In the below tables we evaluate these using factors from an evaluation framework which was created in collaboration with TfNSW. For the complete set of factors, including the non-technical factors, please refer to the main report.

From September to November 2021 articles that support our evaluation criteria have been collected by our team. As frictionless ticketing is an emerging area, direct evidence is still hard to find.

This appendix provides excerpts of academic articles we found that can substantiate the technology gap analysis. We cover the main options, phone (5G), token (UWB), biometrics and wayfinding (SLAM). First, we provide evaluation factors what can be found in terms of academic validation. For evaluation factors that could not be directly validated by academic literature, we have had to use our professional judgement, but these require further research.

We hope that this appendix provides a foundation for current decisions as well as future work.

Contents

Acronyms

#GPP	3rd Generation Partnership Project
ACMA	Australian Communications and Media Authority
AFDO	Australian Federation of Disability Organisations
AI	Artificial Intelligence
AoA	Angle-of-Arrival
AoD	Angle of Departure
API	Application Programming Interface
APPs	Australian Privacy Principles
AR	Augmented reality
ARK	Autonomy Research Kit
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
ATCS	Advanced Train Control Systems
BIBO	Be In Be Out
BICO	Be In, Check out
BLE	Bluetooth Low Energy
BPSK	Binary Phase Shift Keying
BS	Base Station
CAPEX	Capital Expenditures
CBP	Customs and Border Protection
CCC requirements	Car Connectivity Consortium requirements
CCCS	Command Control and Communications Systems
CCOPS	Community Control Over Police Surveillance
CIBO	Check In Be OUT
CiCo	Check-in/Check-out
CRC	Cyclic Redundancy Check
D2D	Device to Device
DAFE	Digital/Analog Front End
DL	Downlink
DL-AoD	Downlink Angle-of-Departure
DoI	Diffusion of Innovations
DPA	Data Protection Act
DSP	Digital Signal Processing
EER	Equal Error Rate
EKF	Extended Kalman Filter
ELS	Enhanced Location Service
EME	Electromagnetic Energy
ERM	Electromagnetic compatibility and Radio spectrum Matters
ETSI Standard	European Telecommunications Standards Institute Standard
FAR	False Acceptance Rate
FCC	Federal Communications Commission
FEC	Forward Error Correction
FIVE	Face in Video Evaluation
FMR	False Match Rate
FNMR	False Non-Match Rate
FPGAs	Field-Programmable Gate Arrays
FP-Node	Floor Plane Node
FRMCS	Future Railway Mobile Communication System

FRR	False Rejection Rate
FRSs	Face Recognition Systems
FRVT	Face Recognition Vendor Tests
FTM	Fine-Time-Measurement
FWG	Functional Working Group
GDPR	General Data Protection Regulation
GNSS	Global Navigation Satellite System
HF	High Frequency
HRIP Act	Health Records and Information Privacy Act 2002
IaaS	Infrastructure as a Service
ICNIRP	The International Commission on Non-Ionising Radiation
ICP	Iterative Closest Point
IEEE	Institute of Electrical and Electronics Engineers
IJB	IARPA Janus Benchmarks
IMU	Inertial Measurement Unit
IoT	Internet of Things
IPS	Indoor Positioning System
IR	Impulse Radio
IR-UWB	Impulse Radio Ultra-Wide Band
iSims	Integrated SIM
ITS	Intelligent Transportation Systems
ITSp	Intelligent Transportation Spaces
LF-RFID	Low frequency radio frequency identification
LFSR	Linear Feedback Shift Register
LMF	Location management function
LoRa	Long-Range
LS	Least Squares
LTE	Long Term Evolution
Maas	Mobility as a Service
MAC	Media Access Control
MBOA	Multiband OFDM alliance
MEC	Multi-access Edge Computing
MIMO	Multiple-Input Multiple-Output
M-MTC	Massive Machine-Type Communication
MN	Moving Networks
MSK	Minimum-Shift Keying
MSL	Mining Systems Laboratory
MT	Maximum-Throughput
MTA	Metropolitan Transit Authority
MB	Multiband
navCOM	Navigational Command
navMSG	Navigational Message
NDT	Normal Distributions Transform
NFC	Near Field Communication
NG-RAN	Next Generation Radio Access Network
NIST	National Institute of Standards and Technology
NLoS	Non-line-of-sight
NR	New radio
OFDM	Orthogonal frequency division multiplexing
oGLs	Object-level graphlets

OOK	On-off Keying
OPEX	Operating expenses
OTDOA	Observed time Difference of Arrival
PaaS	Platforms as a Service
PAM	Pulse Amplitude Modulation
PDCN	Physical Disability Council of NSW
PDoA	Phase-difference-of-Arrival
PE	Pose Estimation
POS	Point-of-sale Systems
PPB	Pilot Parliaments Benchmark
PPIPA	Privacy and Personal Information Protection Act
PPM	Pulse Position Modulation
PR	Pseudo Random
PRSs	Positioning Reference Signals
PTC	Positive Train Control
PWD	People with Disability
PWM	Pulse Width Modulation
RAT	Radio Access Technology
RF	Radio frequency
RFICs	Radio Frequency Integrated Circuits
RFID	Radio frequency identification
RRLT	Redundant Radio Localization and Tracking
RS	Reference signal
RSRP	Reference Signal Received Power
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
RSU	Road Side Infrastructure/Units
RTLS	Real-time Locating System
RTT (1)	Return Travel Time
RTT (2)	Round-Trip-Timing
RU	Radio Units
SaaS	Software as a Service
SAFD	Scale-aware Face Detection
SBAS	Space Based Augmentation System
sGLs	spatial-level graphlets
SLAM	Simultaneous Location and Mapping
SON	Self-Optimising Networks
SRD	Short Range Devices
SRS	Sounding Reference Signal
SSLS	Sub-sampling Least Squares
TAM	Technology Acceptance Model
TDoA	Time-difference of Arrival
TfNSW	Transport for New South Wales
TG	Task Groups
TH-BPSK	Time-Hopping Binary Phase Shift Keying
TH-PPM	Time-Hopping Pulse Position Modulation
ToF	Time-of-Flight
TWR	Two-way Ranging
UAVs	Unmanned Aerial Vehicles
UDN	Ultra-Dense Networks

UE	User Equipment
UGV	Unmanned Ground Vehicle
UHF	Ultra-high frequency
UHF-RFID	Ultra-high frequency radio frequency identification
UL-AOA	Uplink angle-of-arrival
UL-TDOA	Uplink Time Difference of Arrival
U-MTC	Ultra-reliable Machine-Type Communication
URA	Uniform Rectangular Array
URLLC	Ultra-Reliable Low Latency Communications
URS	User Requirements Specification
UTAUT	Unified Theory of Acceptance and Use of Technology
UWB	Ultra-wide band
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
WAN	Wide Area Networking
WCG	Weighted Centroid Geometric
WHO	World Health Organisation
WiWo	Walk-in/Walk-out
WLAN	Wireless Local Area Network
WM5G	West Midlands 5G
WMM	West Midlands Metro
WPAN	Wireless Personal Area Network

5G

As 5G today isn't available in its form needed to provide micro positioning, this particular use case needs real world testing when the required standards become available over the next few years. Recent studies test the phone as a tool for ticketing, using a combination of 4G, GPS and Bluetooth that receive positive end user feedback. Furthermore, 5G NR (5G New Radio) is tested for indoor positioning and in ITS (Intelligent Transport Systems) studies, in order to develop the configuration, the required algorithms and confirm accuracy.

5G Evaluation criteria

Table 1. Key evaluation requirements- 5G (phone app based)

Key evaluation requirements	
Technology readiness – now vs. emerging	Essential capacities proven in positioning indoors and outdoors [1-4]
Certainty/reliability (e.g., interference)	High level of reliability Resilient to interference and multi-path
Accurate/very low error rates	Outdoor (High-speed) under 4m accuracy [3] Indoor (Low-speed) under 10cm accuracy [4]
Secure– not easy to forge, clone	Secure with end-to-end encryption. Private position data acquisition using 5G NR.

Use case requirement	**Tech solution (Note: there is little academic validation of this us case to date)**
Identification	Account numbers can be used for identification. User required to sign in.
Tokenisation /Authentication	Internet Authentication System. Tokenisation can be used in the digital tickets to protect user privacy.

Positioning & trip definition: Registration in (begin of ticket) Registration out (end of ticket) Repeat for next leg of trip	Phone application uses position data and time for taking decisions and issuing tickets. 5G NR Rel-16 will feature NR positioning system for indoors and outdoors with high accuracy. It is expected that NR positioning has a lower battery usage than GNSS and Enhanced Position System (e.g., Google Location), while positioning accuracy is higher. In phase 2 of 5G system (Rel-17), there will be Enhanced NR positioning that has a significant accuracy improvement of under 10 cm. For train station: Virtual zones at stations for automatic check in/out For Buses: Area inside the bus For Taxies: Phone app records travelled distance and elapsed time to calculate the fee
Capacity to process multiple entries simultaneously (large quantities / high throughput) – unless separate lane	Limited to 5G NR coverage and user capacity of cellular providers. (I.e., Cellular capacity could be full, e.g, during New Year Eves) There might be some friction in ticketing and payments, if 5G NR network is not available. A secure local storage can be used on phones during network issues to facilitate the ticketing locally on user phones
Can detect entry in vehicle (as opposed to walking by). Determines with high accuracy which mode of transport has been/is being used	If vehicle boundaries are specified in three dimensions (required algorithms to process positional overlaps in 3D spaces) or a complementary technology is used
Execute gate open and close 'just in in time' for gated solutions Consider gated and non-gated – in a variety of use cases: bus, train, tram, ferry, taxi, on demand	More research required in using 5G NR suitability and network latency for just-in-time gated solution.
Works indoor and outdoor (with and without GPS)	Yes, it will work RAT-independent. Also, 5G NR Rel-16 positioning is user privacy friendly. Because the positioning system of users' devices don't' need to transmit any signal to any service providers, such as, cell tower or Google Location. 5G NR Rel-15: Support for RAT-independent positioning techniques and Observed Time Difference of Arrival (OTDOA) on LTE carriers. 5G NR Rel-16: Support native positioning support by introducing RAT-dependent positioning schemes. According to some lectures, 5G NR positioning has low latency and high accuracy (under 10cm), however there might be some limits and government regulations on latency and accuracy of positioning for commercial use.
Cover fixed and variable routes, i.e., cannot rely on fixed infrastructure. Work in taxi's, mini buses, mopeds, bike sharing, etc.	Yes, it can cover a wide variety of transports. Cloud-base or local intelligent can calculate most suitable fare. In phones, a service can be run at the background to sends status and updates to backend in Realtime. Also, temporarily trip data can be stored on the phone securely for off-time sync, in case of connection loss.
High feasibility of installation across all use cases	Yes, by using services from App Store, Google Store and QR codes

Low maintenance/Asset Management System (also Resistant to vandalism)	Low Maintenance and no requirement of new infrastructure installation for TfNSW. Easy implementation and straight development using Continuous Development (CD) and Continuous Integration (CI)

Risks/concerns?	- Dependent on network roll out by Telco providers. Coverage of 5G network. May require a redundancy option - Dependent roll out in end user market - In vehicle accuracy - Outdoor accuracy when moving

5G Literature overview

Tech Type	Reference	Summary	Key Point of Interest
1. 5G standard	3GPP. (2020). Release 17. Retrieved 2022, from https://www.3gpp.org/release-17	5G- New Radio standards R17	- 5G NR Positioning Enhancement - 5G Rel-17 Specifications - 5G Rel-17 timeline - 5G Rel-17 progress status
2. 5G standard	3GPP. (2020). Release 16. Retrieved 2022, from https://www.3gpp.org/release-16	5G- New Radio standards R16	- 5G NR Positioning - 5G Rel-16 Specifications - 5G Rel-16 timeline - 5G Rel-16 progress status
3. 5G positioning and location aware	Koivisto, M., Hakkarainen, A., Costa, M., Kela, P., Leppanen, K., & Valkama, M. (2017). High-Efficiency Device Positioning and Location-Aware Communications in Dense 5G Networks. IEEE Communications Magazine, 55(8), 188 - 195.	In this article, the prospects and enabling technologies for high-efficiency device positioning and location-aware communications in emerging 5G networks are reviewed. We will first describe some key technical enablers and demonstrate by means of realistic ray-tracing and map based evaluations that positioning accuracies below one meter can be achieved by properly fusing direction and delay related measurements on the network side, even when tracking moving devices. We will then discuss the possibilities and opportunities that such high-efficiency positioning capabilities can offer, not only for location-based services in general, but also for the radio access network itself.	We will demonstrate that geometric location-based beamforming schemes become technically feasible, which can offer substantially reduced reference symbol overhead compared to classical full channel state information (CSI)-based beamforming. At the same time, substantial power savings can be realized in future wideband 5G networks where acquiring full CSI calls for wideband reference signals while location estimation and tracking can, in turn, be accomplished with narrowband pilots.
4. 5G New radio 3D UE positioning	Sun, B., Tan, B., Wang, W., & Lohan, E. S. (2021). A Comparative Study of 3D UE Positioning in 5G New Radio with a Single Station. Sensors, 21(4), 1178.	This paper is a pilot study of using 5G uplink physical layer channel sounding reference signals (SRSs) for 3D user equipment (UE) positioning. The 3D positioning capability is	The positioning performance of both algorithms is evaluated by estimation of the root mean squared error (RMSE) versus the varying signal-to-noise-ratio

		backed by the uniform rectangular array (URA) on the base station and by the multiple subcarrier nature of the SRS. In this work, the subspace-based joint angle-time estimation and statistics-based expectation-maximization (EM) algorithms are investigated with the 3D signal manifold to prove the feasibility of using SRSs for 3D positioning.	(SNR), the bandwidth, the antenna array configuration, and multipath scenarios. The simulation results show that the uplink SRS works well for 3D UE positioning with a single base station, by providing a flexible resolution and accuracy for diverse application scenarios with the support of the phased array and signal estimation algorithms at the base station.
5. 5G Accurate positioning for C-V2X	Liu, Q., Liang, P., Xia, J., Wang, T., Song, M., Xu, X., ... & Liu, L. (2021). A Highly Accurate Positioning Solution for C-V2X Systems. Sensors, 21(4), 1175.	In this paper, key performance indicators (KPIs) for C-V2X positioning have been described firstly. Then positioning challenges and conventional positioning methods for C-V2X are reviewed. Afterward, two user equipment (UE)-based and UE-assisted C-V2X positioning architectures are proposed, and key technologies are also described. Lastly, testing and typical application cases are provided.	Cellular vehicle-to-everything (C-V2X) is essential in enabling safe, reliable, and efficient transportation services. It serves as serve as the foundation for vehicles to communicate with each other and everything around them. One fundamental element in C-V2X is positioning, namely extracting the vehicle's absolute and relative positions concerning other objects such as buildings, pedestrians, traffic signs, and other vehicles. However, its feasibility in enabling vehicular positioning has not been fully explored yet.
6. Wi-Fi, 3G/4G, GPS technology for mobile payment, route planner	Ferreira, M. C., Fontesz, T., Costa, V., Dias, T. G., Borges, J. L., & e Cunha, J. F. (2017). Evaluation of an integrated mobile payment, route planner and social network solution for public	The Seamless Mobility platform integrates three main components: (i) mobile payments, (ii) route planner, and (iii) social network. The payment component is based on the pay-as - you-go concept with check-in and check-out requiring the reading of the corresponding QR	Mobile application, called One Ride, developed for Android and IOS devices. It uses QR Codes technology combined with location providers (GPS) and wireless communication technologies (3G, 4G or Wi-Fi). This application was

	transport. Transportation research procedia, 24, 189-196.	Code station. To test the concept, a mobile application, called One Ride, was developed. This application was tested by users in real environment, in the city of Porto, Portugal.	tested by potential users and experts in both laboratory and real environment. The proposed mobile ticketing system is based on the pay-as-you-go approach. The passenger only needs to indicate the entry points in each means of transport of a given trip (check-in) and the completion of the same (check-out). The technologies chosen for the check-in/check-out process with the mobile phone were the QR Codes combined with location providers (GPS) and wireless communication technologies (3G, 4G or Wi-Fi). The use of the QR Codes to perform the payment has shown to be one of the main challenges to be addressed, since lighting conditions, position, and distance to the QR Code influences the reading process.
7. Wi-Fi, 3G/4G, GPS technologies to use for mobile ticketing for public transport	Ferreira, M. C., Nóvoa, M. H., & Dias, T. G. (2013, February). A proposal for a mobile ticketing solution for metropolitan area of oporto public transport. In International Conference on Exploring Services Science (pp. 263-278). Springer, Berlin, Heidelberg.	The proposed system must require the minimum investment cost from the PTOs and travellers' point-of-view, achieving at the same time the maximum consumer acceptance possible. to achieve this goal decisions had to be made considering the most suitable technologies for the AMP network, which led to Wi-Fi and GPS technologies. purchase and validation of tickets will be made over-the-air, and the GPS technology will be used to locate the traveller	In public transport services, contactless ticketing and payment solutions showed an increase in traveller satisfaction due to its easy and convenient characteristics. The electronic ticketing system in AMP is an open (ungated) system that required a significant technological investment, such as card readers along the platforms at each metro station and at

			each bus vehicle, and handheld devices for conductors. in the proposed system, the purchase and validation of tickets will be made over-the-air, and the GPS technology will be used to locate the traveller and reduce the number of options when it comes to purchase or validate a ticket, making the system easier to use. According to the usability testing results, all users completed all tasks successfully. Older people and non-technological professionals (e.g., lawyers) took more time to perform the tasks than the others, but they all found “easy” or “very easy” to perform most of the tasks. Contains a table which presents the factors Influencing Mobile Payment Adoption.
8. 5G Standard	5G Release 15 (2019). https://www.3gpp.org/release-15	Official features and information about 5G Release 15	- 5G Rel-15 Specifications - 5G Rel-15 timeline - 5G Rel-15 progress status
9. 5G NR indoor positioning	Lu, Y., Koivisto, M., Talvitie, J., Valkama, M., & Lohan, E. S. (2019, September). EKF-based and geometry-based positioning under location uncertainty of access nodes in indoor environment. In 2019 International Conference on Indoor Positioning and Indoor Navigation (IPIN) (pp. 1-7). IEEE.	This paper presents and formulates two positioning algorithms when the location uncertainty of the access nodes (ANs) is taken into consideration. The first algorithm is a low-complexity geometry-based 3D positioning algorithm that utilizes both time-of-arrival and angle-of-arrival measurements. The second algorithm relies on extended Kalman Filter (EKF)-based positioning, by mapping the ANs' location	Based on the conducted complexity analysis, the proposed geometry-based algorithm is computationally more efficient than the EKF-based algorithm. In addition, the proposed geometry-based positioning method demonstrates a higher robustness against a high location uncertainty of

		uncertainty into the measurement noise statistics.	ANs than the considered EKF-based method.
10. 5G NR vision: NGMN-5G initiative	Annunziato, A. (2015, May). 5G vision: NGMN-5G initiative. In 2015 IEEE 81st Vehicular Technology Conference (VTC Spring) (pp. 1-5). IEEE.	The fifth generation of mobile technology (5G) is positioned to address the demands and business contexts of 2020 and beyond. It is expected to enable a fully mobile and connected society and to empower socio-economic transformations in countless ways many of which are unimagined today, including those for productivity, sustainability and well- being.	The demands of a fully mobile and connected society are characterized by the tremendous growth in connectivity and density/volume of traffic, the required multi-layer densification in enabling this, and the broad range of use cases and business models expected.
11. 5G NR vision and standardization	Koripi, M. (2021). 5G Vision and 5G Standardization. Parishodh Journal, 10, 62-66.	Wireless networks offer lots of purposes. In many cases, they are made use of as cord replacements, while in various other instances they are actually used to deliver accessibility to business information coming from distant areas. The wireless structure could be constructed for quite a little price contrasted to standard wired options.	Yet building wireless networks is simply partly about saving funds. Through supplying folks in your neighbourhood community along with less costly as well as simpler accessibility to relevant information, they are going to straight profit from what the Net needs to use. The time, as well as attempt conserved through possessing accessibility to the global network of details, translates into wide range on a nearby range, as more work could be done in a lot less opportunity as well as with much less effort.
12. 5G for next generation communication network and services	The 5G Infrastructure Public Private Partnership the next generation of communication networks and services. https://5g-ppp.eu/wp-content/uploads/2015/02/5G-Vision-Brochure-v1.pdf	Future European society and economy will strongly rely on 5G infrastructure. The impact will go far beyond existing wireless access networks with the aim for communication services, reachable everywhere, all the time, and faster.	5G is an opportunity for the European ICT sector which is already well positioned in the global R&D race. 5G technologies will be adopted and deployed globally in alignment with developed and emerging markets' needs.

13. 5G research directions from METIS project	Osseiran, A., Boccardi, F., Braun, V., Kusume, K., Marsch, P., Maternia, M., ... & Fallgren, M. (2014). Scenarios for 5G mobile and wireless communications: the vision of the METIS project. IEEE communications magazine, 52(5), 26-35.	In this article, we describe the scenarios identified for the purpose of driving the 5G research direction. Furthermore, we give initial directions for the technology components (e.g., link level components, multinode/multiantenna, multi-RAT, and multi-layer networks and spectrum handling) that will allow the fulfillment of the requirements of the identified 5G scenarios.	METIS is the EU flagship 5G project with the objective of laying the foundation for 5G systems and building consensus prior to standardization. The METIS overall approach toward 5G builds on the evolution of existing technologies complemented by new radio concepts that are designed to meet the new and challenging requirements of use cases today??s radio access networks cannot support. The integration of these new radio concepts, such as massive MIMO, ultra dense networks, moving networks, and device-to-device, ultra reliable, and massive machine communications, will allow 5G to support the expected increase in mobile data volume while broadening the range of application domains that mobile communications can support beyond 2020.
14. 5G dense network positioning and location aware	Koivisto, M., Hakkarainen, A., Costa, M., Kela, P., Leppanen, K., & Valkama, M. (2017). High-efficiency device positioning and location-aware communications in dense 5G networks. IEEE Communications Magazine, 55(8), 188-195.	In this article, the prospects and enabling technologies for high-efficiency device positioning and location-aware communications in emerging 5G networks are reviewed. We will first describe some key technical enablers and demonstrate by means of realistic ray-tracing and map based evaluations that positioning accuracies below one meter can be achieved by properly fusing direction and delay related measurements on the network side, even when	In particular, we demonstrate that geometric location-based beamforming schemes become technically feasible, which can offer substantially reduced reference symbol overhead compared to classic full channel state information (CSI)-based beamforming. At the same time, substantial power savings can be realized in future wideband 5G networks where acquiring full CSI calls

		tracking moving devices. We will then discuss the possibilities and opportunities that such high-efficiency positioning capabilities can offer, not only for location-based services in general, but also for the radio access network itself.	for wideband reference signals while location estimation and tracking can, in turn, be accomplished with narrowband pilots.
15. 5G mmW networking and positioning	Rastorgueva-Foi, E., Galinina, O., Costa, M., Koivisto, M., Talvitie, J., Andreev, S., & Valkama, M. (2020). Networking and Positioning Co-Design in Multi-Connectivity Industrial mmW Systems. IEEE Transactions on Vehicular Technology, 69(12), 15842-15856.	Highly directional millimeter-wave (mmW) connectivity - especially in industry-grade scenarios with complex and unpredictable device mobility - requires a certain degree of structural redundancy in the network, which can be provided by utilizing multi-connectivity mechanisms. To lower the coordination complexity and overhead of tracking multiple directional beams, mmW networks can retrieve and leverage timely positioning information. In this paper, we develop a holistic framework for the co-design of networking and positioning in industrial 5G mmW deployments with multi-connectivity capabilities. In particular, we propose a flexible two-stage positioning solution - mindful of information uncertainty - that relies upon the 5G NR system design and can be seamlessly integrated into the mmW cellular infrastructure with reasonable overheads.	We reproduce a typical 5G mmW network deployment featuring dissimilar device mobility patterns and assess the performance of the proposed architecture. In particular, we evaluate the precision of our positioning and base station orientation estimation methods as well as analyze the impact of the proposed scheme on the system-level performance. Our numerical results demonstrate that the proposed solution yields highly accurate position estimates and significantly improves the average network spectral efficiency.
16. 5G NR mm wave downlink vehicular positioning	Wymeersch, H., Garcia, N., Kim, H., Seco-Granados, G., Kim, S., Wen, F., & Fröhle, M. (2018, December). 5G mm wave downlink vehicular positioning. In 2018 IEEE Global Communications Conference (GLOBECOM) (pp. 206-212). IEEE.	5G new radio (NR) provides new opportunities for accurate positioning from a single reference station: large bandwidth combined with multiple antennas, at both the base station and user sides, allows for unparalleled angle and delay resolution. Nevertheless, positioning quality is affected by multipath and clock biases. We	We find that when a sufficient number of paths is present, a vehicle can still be localized thanks to redundancy in the geometric constraints. Moreover, the 5G NR signals enable a vehicle to build up a map of the environment.

		study, in terms of performance bounds and algorithms, the ability to localize a vehicle in the presence of multipath and unknown user clock bias.	
17. 5G NR mmWave massive MIMO systems	Ma, W., Qi, C., & Li, G. Y. (2020). High-resolution channel estimation for frequency-selective mmWave massive MIMO systems. IEEE Transactions on Wireless Communications, 19(5), 3517-3529.	In this paper, we develop two high-resolution channel estimation schemes based on the estimating signal parameters via the rotational invariance techniques (ESPRIT) method for frequency-selective millimeter wave (mmWave) massive MIMO systems. The first scheme is based on two-dimensional ESPRIT (TDE), which includes three stages of pilot transmission. This scheme first estimates the angles of arrival (AoA) and angles of departure (AoD) and then pairs the AoA and AoD. The other scheme reduces the pilot transmission from three stages to two stages and therefore reduces the pilot overhead. It is based on one-dimensional ESPRIT and minimum searching (EMS).	It first estimates the AoD of each channel path and then searches the minimum from the identified mainlobe. To guarantee the robust channel estimation performance, we also develop a hybrid precoding and combining matrices design method so that the received signal power keeps almost the same for any AoA and AoD. Finally, we demonstrate that the proposed two schemes outperform the existing channel estimation schemes in terms of computational complexity and performance.
18. 5G NR mmWave tracking method for angle estimation	Hu, C. N., Xu, W. J., Gao, R. Z., Cai, Z. T., Chen, X. Z., Wu, C. C., & Lo, P. (2020, August). Monopulse Tracking Method for Angle Estimation in 5G Millimeter-Wave Channel Sounder. In 2020 International Workshop on Electromagnetics: Applications and Student Innovation Competition (iWEM) (pp. 1-2). IEEE.	This study numerically and experimentally investigate the use of monopulse tracking algorithm for angle estimation in Channel Sounder system by using a 2×4 millimeterwave (mmWave) antenna module operating at 28 GHz.	5G Millimeter-Wave for Monopulse Tracking
19. 5G NR IoT supporting network slicing	Ni, J., Lin, X., & Shen, X. S. (2018). Efficient and secure service-oriented authentication supporting network	5G network is considered as a key enabler in meeting continuously increasing demands for the future Internet of Things (IoT) services,	Users can efficiently establish connections with 5G core network and anonymously access IoT services under

	slicing for 5G-enabled IoT. IEEE Journal on Selected Areas in Communications, 36(3), 644-657.	including high data rate, numerous devices connection, and low service latency. To satisfy these demands, network slicing and fog computing have been envisioned as the promising solutions in service-oriented 5G architecture. However, security paradigms enabling authentication and confidentiality of 5G communications for IoT services remain elusive, but indispensable. In this paper, we propose an efficient and secure service-oriented authentication framework supporting network slicing and fog computing for 5G-enabled IoT services.	their delegation through proper network slices of 5G infrastructure selected by fog nodes based on the slice/service types of accessing services. The privacy-preserving slice selection mechanism is introduced to preserve both configured slice types and accessing service types of users. In addition, session keys are negotiated among users, local fogs and IoT servers to guarantee secure access of service data in fog cache and remote servers with low latency. We evaluate the performance of the proposed framework through simulations to demonstrate its efficiency and feasibility under 5G infrastructure.

Ultra-Wide Band

This technology is not new but is enjoying a resurgence due to the demand for accurate locationing. Research has been available for several decades focusing on the accuracy and comparing it to alternatives. This has driven the adoption of UWB (Ultra-wide band) in industry applications. Di Benedetto, M. G. (Ed.) published the standard book on UWB back in 2006.

Recent research is focusing on new applications, including transport where payment, positioning and obstacle detection are tested on trains. Recent research focuses on the deployment of UWB in public transport, for instance to assist travellers prior about the bus arrival time, using Bluetooth Low Energy (BLE) UWB beacons to notify the commuters about arriving bus at the bus stop.

Use cases that have been published include obstacle avoidance for people with disability, inflight cockpit communications, people counting and indoor positioning

UWB tokens and end user wearables are adopted by major phone brands and developed by major device manufacturers, but the particular use case of frictionless ticketing for public transport requires further real-world research.

UWB: Evaluation criteria

Table 2. Key evaluation requirements- UWB (wearable tag)

Key evaluation requirements	
Technology readiness – now vs. emerging	Proven in another use case for precision indoor location tracking and RTLS (real-time location system) Commercial products available (Ubisense, decawave, sewio) for indoor location tracking (RTLS) -tested in [1,2]
Certainty/reliability (e.g., interference)	Ultra-reliable Resilient to interference and multi-path
Accurate/very low error rates	Accurate, centimetre level (upto 10cm) precision [3, 4] Use ToF and AoA technique Real-time low latency
Secure– not easy to forge, clone	Secure with PHY level encryption Use Time of Flight (ToF), resilient to replay attack

Use case requirement	**Tech solution**
Identification	Tag Unique Id will be identified and tracked using Anchors (installed on infrastructure)
Tokenisation /Authentication	- The tag location is calculated at installed anchors, tokenisation is done between anchors towards backend - Encryption at application level can be implemented

	- Low level (PHY) encryption supported in IEEE 802.15.4z to handle relay attack
Positioning & trip definition: Registration in (begin of ticket) Registration out (end of ticket) Repeat for next leg of trip	Suitable for gated scenario to open gates, and automatic detection at ungated scenarios - Precise RTLS (real-time location tracking is possible with infrastructure and backend server [4] - Automatic begin and end of trip possible at entry/exit gates - Alternative notification can be given via beep or sms
Capacity to process multiple entries simultaneously (large quantities / high throughput) – unless separate lane	Accuracy and number of tags tracked simultaneously is relative to number and type of anchor configuration: Approx. 500 with 4 anchors (Full RTLS mode) Approx. 50 with 2 anchors
Can detect entry in vehicle (as opposed to walking by). Determines with high accuracy which mode of transport has been/is being used	Can detect precision 3D position within the defined area within detection coverage [3] - Can detect tags across walls, so beam angle is important to define coverage area - UWB anchors on one train/bus should be time synced with each other
Execute gate open and close 'just in in time' for gated solutions Consider gated and non-gated – in a variety of use cases: bus, train, tram, ferry, taxi, on demand	Just in time gate on/close possible due to precision tracking in 3D [4] Suitable for gated entry for opening gates with precision tracking Entry/exit areas should be within coverage of installed anchors Suitable for train, tram, bus, ferry
Works indoor and outdoor (with and without GPS)	Works anywhere with required fixed installations and connectivity
Cover fixed and variable routes, i.e., cannot rely on fixed infrastructure. Work in taxi's, mini buses, mopeds, bike sharing, etc.	Need fixed infrastructure (with power and n/w connectivity) – min 2 anchors required Train stations – Ok either at gate or in train Buses – Ok with 2 anchors Taxi – Not known yet, bike sharing stand – Not known yet
High feasibility of installation across all use cases	Range varies from 20m (non-line of sight) to 150m (line of sight) –[4], installation is mandatory for coverage as per use case either for identification or real-time tracking
Low maintenance/Asset Management System (also Resistant to vandalism)	To be investigated

Risks/concerns?	- Connected Anchors installation required - Accuracy is determined by number of anchors - Minimum 2 anchors for 2D accuracy - 3-4 anchors for 3D positional accuracy and tracking

UWB: Literature overview

Tech Type	Reference	Summary	Key Point of Interest
1. UWB realtime locating system	Chantaweesomboon, W., Suwatthikul, C., Manatrinon, S., Athikulwongse, K., Kaemarungsi, K., Ranron, R., & Suksompong, P. (2016). On performance study of UWB real time locating system. Bangkok, Thailand: IEEE.	This work presents a performance study on location accuracy of DecaWave's TREK1000, a two-way ranging RTLS IC evaluation kit. Four anchors and one tag were set up as an RTLS deployed in two different indoor areas.	The difficulties encountered during the calculation of the tag's location at certain locations were pointed out. It was also found that the change in performance of the 2D localization of the system when set up with three and four anchors was insignificant. Additionally, the accuracy in the third dimension or the height of the tag above the ground was found to be less accurate.
2. UWB Indoor performance analysis	Ruiz, A. R., & Granja, F. S. (2017). Comparing Ubisense, BeSpoon, and DecaWave UWB Location Systems: Indoor Performance Analysis. IEEE Transactions on Instrumentation and Measurement , 66(8), 106 - 2117.	In this paper, we compare three commercially available UWB systems (Ubisense, BeSpoon, and DecaWave) under the same experimental conditions, in order to do a critical performance analysis. We include the characterization of the quality of the estimated tag-to-sensor distances in an indoor industrial environment.	The study also includes the analysis of the estimated azimuth and elevation angles for the Ubisense system, which is the only one that incorporates this feature using an array antenna at each sensor. Finally, we analyze the 3-D positioning estimation performance of the three UWB systems using a Bayesian filter implemented with a particle filter and a measurement model that takes into account bad range measurements and outliers.
3. UWB real-time location systems for smart factory	Barbieri, L., Brambilla, M., Pitic, R., Trabattoni, A., Mervic, S., & Nicoli, M. (2020). UWB Real-Time Location Systems for Smart Factory: Augmentation Methods and Experiments. London, UK: IEEE.	In this paper, we focus on Bayesian filtering techniques to counterbalance the detrimental effects induced by non line of sight and dense multipath in a smart factory scenario. We first conduct a set of experimental tests with commercial devices in an industrial facility of Pirelli Tyre S.p.A. located in Milan, Italy. We then use the collected data to design and test augmentation algorithms based on Extended	Experimental results show that, despite the harsh environment, accurate localization is possible by fusion of hybrid measurements and integration of prior information on the target dynamics and the industrial propagation environment.

			Kalman Filter (EKF) and Particle Filter (PF), fusing Time Difference of Arrival (TDoA) and Angle of Arrival (AoA) signals.	
4.	UWB for intelligent transport system	University at Albany - SUNY; Center of Technology in Government. (n.d.). Intelligent Transportation based UWB. Albany, New York.	In a series of controlled experiments, we evaluated the feasibility of deploying Ultra-Wide Band (UWB) technology using the following use cases: (1) for determining the location of a train on a track (called ranging in the experiment) and (2) for an electronic payment application, such as a passenger at a turnstile, to determine the ability to locate individuals within crowds (called localization in the experiment). Both cases were tested indoors (tunnel) and outdoors (roadway) to evaluate environmental effects.	Based on the findings above, we recommend further prototyping of IR-UWB in real-world metropolitan public transporation scenarios scenarios with objective monitoring and evaluation of results. Our experiments validate the promise of IR-UWB to satisfy the use case requirements for ranging and localization, but these need to be further tested and affirmed to both extend the scenarios of our controlled lab and to address the cautions noted below.
5.	UWB real-time location system for smart factory	Barbieri, L., Brambilla, M., Pitic, R., Trabattoni, A., Mervic, S., & Nicoli, M. (2020, August). UWB real-time location systems for smart factory: augmentation methods and experiments. In 2020 IEEE 31st Annual International Symposium on Personal, Indoor and Mobile Radio Communications (pp. 1-7). IEEE.	In Industry 4.0, real-time location systems are emerging as a key technology to improve the efficiency of industrial processes, as they allow to track any assets or material movement and collect data on their usage. Ultra Wideband (UWB) systems offer unrivalled localization accuracy, but they call for augmentation strategies in environments with complex propagation conditions such as plants or factories with high density of scattering objects and obstructions. In this paper, we focus on Bayesian filtering techniques to counterbalance the detrimental effects induced by non-line of sight and dense multipath in a smart factory scenario. We first conduct a set of	Smart factory applications require precise positioning, as envisioned by Industry 4.0. In this paper, we first compared commercial UWB devices (Ubisense and Sewio), showing their localization accuracy in an industrial plant of Pirelli Tyre S.p.A.. The analysis on static localization scenarios highlights that Ubisense is the most accurate solution, providing an error lower than 40 cm in 95% of cases. On the other hand, Sewio reaches an accuracy of 1.17 m but it has the advantage of a lower price and easier installation and calibration. UWB raw data collected by experiments have been used to validate Bayesian tracking filters for multipath mitigation. The analysis

		experimental tests with commercial devices in an industrial facility of Pirelli Tyre S.p.A. located in Milan, Italy. We then use the collected data to design and test augmentation algorithms based on Extended Kalman Filter (EKF) and Particle Filter (PF), fusing Time Difference of Arrival (TDoA) and Angle of Arrival (AoA) signals. Experimental results show that, despite the harsh environment, accurate localization is possible by fusion of hybrid measurements and integration of prior information on the target dynamics and the industrial propagation environment.	focused on evaluating the impact of the type of measurements (stand-alone TDoA or a combination of TDoA and AoA) as well as of the type of filter (EKF or PF). In all cases, a PF-based tracking technique has been shown to outperform the EKF one. A combination of AoA and TDoA measurements is to be preferred in industrial environments to mitigate the dense multipath propagation.
6. UWB intelligent transport system	Intelligent Transportation based UWB Positioning and Connectivity https://www.albany.edu/sine/assets/docs/UAlbany%20UWB%20Study.pdf	In a series of controlled experiments, we evaluated the feasibility of deploying Ultra-Wide Band (UWB) technology using the following use cases: (1) for determining the location of a train on a track (called ranging in the experiment) and (2) for an electronic payment application, such as a passenger at a turnstile, to determine the ability to locate individuals within crowds (called localization in the experiment). Both cases were tested indoors (tunnel) and outdoors (roadway) to evaluate environmental effects. The experiments measured for reliability (integrity of signal) and precision (range of error in locating) based on impulsive radio UWB (IR-UWB). Our findings,	For ranging in the tunnel environments, our results show that in the majority of cases for line-of-sight distances of up to 150m (~164 yds or 1/10 mile) between two UWB nodes, the precision was within 10cm (~4in). For non-line-of-sight distances up to 26m (~28yds) between two UWB nodes, the precision was within 50cm (~20in).

		recommendations, and cautions are summarized below.	
7. UWB real-time locating system	Chantaweesomboon, W., Suwatthikul, C., Manatrinon, S., Athikulwongse, K., Kaemarungsi, K., Ranron, R., & Suksompong, P. (2016, March). On performance study of UWB real time locating system. In 2016 7th International Conference of Information and Communication Technology for Embedded Systems (IC-ICTES) (pp. 19-24). IEEE.	Real time locating systems (RTLS) with centimeter accuracy have recently been made available for commercial deployment by employing ultra wideband (UWB) technology. DecaWave's DW1000 is a commercial UWB integrated circuit that utilizes time-of-flight (ToF) measurement technique and two-way-ranging (TWR) mechanism to accurately estimate the distance between an anchor and a tag. With the distances between the tag and at least three anchors, a trilateration algorithm can be applied to estimate the tag's location on the same two-dimensional (2D) plane as the anchors. Moreover, if four or more anchors are available, the tag's location in three-dimensional space can also be estimated. This work presents a performance study on location accuracy of DecaWave's TREK1000, a two-way ranging RTLS IC evaluation kit. Four anchors and one tag were set up as an RTLS deployed in two different indoor areas. The difficulties encountered during the calculation of the tag's location at certain locations were pointed out. It was also found that the change in performance of the 2D localization of the system when set up with three and four anchors was insignificant. Additionally, the accuracy in the third	The RTLS evaluation kit tested in this article showed a promising potential for micro-location applications. However, we found some limitations in the performance of UWB RTLS in both 2D and 3D cases. On average the 2D accuracy is within the sub-meter level, but the 3D accuracy could be worse up to 3-meter level. A number of guidelines for deploying the UWB RTLS properly to achieve a good localization performance are pointed out, such as where the anchors should be installed and the suitable area the tag should be within. The need to improve location accuracy along the z-axis is also an important issue to be investigated further in the future

		dimension or the height of the tag above the ground was found to be less accurate	
8. UWB RFID combined locating methods	Núñez Álvarez, C., & Crespo Cintas, C. (2010). Accuracy evaluation of probabilistic location methods in UWB-RFID systems (Master's thesis, Universitat Politècnica de Catalunya).	The present project is focused on investigating the achievable accuracy of classical location methods commonly used in wireless and proposing an alternative location method based on combining two of them. The first part of the project studies the advantages and disadvantages of extending Ultra Wideband and Radiofrequency Identification technologies on some classical location methods. As a result of the study and with the goal of improving accuracy in indoor radio propagation channels, the Received Strength Signal-based location method and the Time Difference Of Arrival-based location method are selected to be combined in the alternative location method, including the proper channel models.	This combined location method takes advantage of the virtues of each location method and combines information in order to improve the estimation of one target's position when locating in indoor channel. The second part of the project is devoted to analyse and simulate the modified RSS, TDOA and Combined location methods, considering the randomness of a real multipath fading channel. Results show that the Combined location method performs always the best accuracy. Specifically in analytical study, the combined location method provides a deterministic error of 24 cm which represents an improvement of 54% and 15% of the RSS and TDOA accuracies respectively. In the simulated study, results show that it is able to improve the accuracy up to 46% and 85% of the RSS and TDOA respectively in specific evaluated points.

9. UWB realtime locating system localisation and identification	Porto, S. M. C., Arcidiacono, C., Giummarra, A., Anguzza, U., & Cascone, G. (2014). Localisation and identification performances of a real-time location system based on ultra wide band technology for monitoring and tracking dairy cow behaviour in a semi-open free-stall barn. Computers and Electronics in Agriculture, 108, 221-229.	The objective of this study was to evaluate the localisation and identification performances of a Real-Time Location System (RTLS) based on Ultra Wide Band (UWB) technology within a semi-open free-stall barn since the conditions of the breeding environment were different from that of the 'typical open environment' used by the RTLS producer to test the system and the building characteristics were dissimilar to those of the indoor environments considered in other tests. Each dairy cow was equipped with an active tag applied to one ear and a reference tag was fixed to a pillar of the barn. A video-recording system was installed in the barn to perform the assessment of the RTLS. Top-view camera images of the area of the barn were rectified and synchronised with the RTLS. An operator validated each position of the cow computed by the RTLS by performing cow visual recognition on the camera images. To perform this validation a software specifically designed for the purpose was utilised. It is an automatic and interactive tool which includes selection and control tabs for data management, visualisation and labelling of the images with the aim of computing tag true positions.	It was equal to about 0.11 m with an identification accuracy of nearly 100% for the reference tag, whereas for the tags applied to the cows the average localisation mean error, computed by averaging the localisation mean errors of the tags, was about 0.515 m with an identification accuracy of 98%. At the 90th percentile the average localisation mean error was about 0.967 m for the cows' tags, whereas it was about 0.17 m for the reference tag.
10. UWB based people counting system	Choi, J. W., Quan, X., & Cho, S. H. (2017). Bi-directional passing people counting system based on IR-UWB radar sensors. IEEE Internet of Things Journal, 5(2), 512-522.	In this paper, we propose system based on impulse radio ultra-wideband (IR-UWB) radar sensors for counting multiple people passing through a passage or a wide door. The proposed counting system utilizes two	Algorithmically, sensing and direction recognition of a person passing through a path are performed considering both information of a received signal in each radar and mutual information between two

		IR-UWB radar sensors equipped with antennas which have narrow beam width to form two invisible electronic layers in the path. The two electronic layers are used for sensing and direction recognition of multiple people passing by.	radar signals. The proposed counting system is implemented with two radar modules designed using commercial radar ICs and a Raspberry Pi 2 module. We installed the designed modules in the subway station to verify the performance. Based on the installed modules, data were acquired for one week and the counting performance was verified for various time intervals such as 2 minutes, 1 hour, and 1 day. Except for a few cases, we could get counting results with errors less than 10%.
11. UWB inbound and outdound detection of people's movement	Quan, X., Choi, J. W., & Cho, S. H. (2014, January). In-bound/Out-bound detection of people's movements using an IR-UWB radar system. In 2014 International Conference on Electronics, Information and Communications (ICEIC) (pp. 1-2). IEEE.	This paper presents an In-bound/Out-bound detection algorithm of people's movements using an impulse radio ultra-wideband (IR-UWB) radar system. This algorithm is based on a simple threshold crossing (TC) method which has been widely used in UWB field.	This algorithm can detect the people who pass through the gate field. It can be used in gate monitoring to count the number of people in a large room.
12. UWB counting algorithms for multiple objects	Choi, J. W., Kim, J. H., & Cho, S. H. (2012, September). A counting algorithm for multiple objects using an IR-UWB radar system. In 2012 3rd IEEE international conference on network infrastructure and digital content (pp. 591-595). IEEE.	In this paper, a counting algorithm is proposed based on the signal's local maximum values of power signals and positions. After background subtraction process to eliminate clutter signals, several positions and values of the signal's local maximum values are searched for some prefixed number of frames.	After sufficient values are stored in a buffer, an average of the values is calculated. Among the values, the number of values exceeding the thresholds is counted and stored as 1-st decided targets' number. To improve the performance we vote with some 1-st decided targets' number. We prove this algorithm's performance by some experiments. Simulation results are included experimented in the 6 m by 6 m indoor environment.

13. UWB estimating crowd density	Yuan, Y., Zhao, J., Qiu, C., & Xi, W. (2013). Estimating crowd density in an RF-based dynamic environment. IEEE Sensors Journal, 13(10), 3837-3845.	In this paper, we introduce a low cost crowd density estimating method using wireless sensor networks. The proposed approach is a device-free crowd counting approach without objects carrying any assistive device. It is hard to count objects based on RSS measurement, since different number of mobile people at different positions often generates different RSS due to the multipath phenomenon. This paper utilizes the space-time relativity of crowd distribution to reduce the estimation errors.	The proposed approach is an iterative process, which contains three phases: the training phase, the monitoring phase, and the calibrating phase. Our experiments are implemented based on TelosB sensor platform. We also do some large-scale simulations to verify the feasibility and the effectiveness of our crowd density estimating approach.
14. UWB counting system	Bartoletti, S., Conti, A., & Win, M. Z. (2017). Device-free counting via wideband signals. IEEE Journal on Selected Areas in Communications, 35(5), 1163-1174.	Counting people and things (targets) in a monitored area, also known as crowd-counting, enables several applications in diverse scenarios, including smart building, intelligent transportation, and public safety. This paper proposes a mathematical framework for the design of device-free counting systems. First, a maximum a posteriori algorithm is developed for counting via wideband signal backscattering by relying on model order selection. Then, a method that relies on low-level features is proposed to lower the computational complexity.	The proposed method is verified via sample-level simulations in realistic operating conditions and compared with current solutions.
15. UWB for railway tunnels	Mahobe, M. (2013). UWB Radio Wireless Communication System Design for Railway Tunnels (Doctoral dissertation).	Railway is an economical and comfortable mode of transportation for long distances. Huge population from all over the world depends on it for their daily routine. We evaluated the frequency response, channel	All the channel characteristics show that UWB systems perform better than the existing techniques. So to maintain the continuity of data stream we need to install UWB trans-receiver over the specific

		impulse response and path loss for different distances between transmitter and receiver and observed the effect of fading over the channel. Then three standard wave shapes has been tested with the modelled channel. It is to observe the phase shift and time delay provided by the considered channel model which behaves as a multipath fading channel with additive white Gaussian noise. To check the quality of reception bit error rate performance has been evaluated for BPSK and OOK modulation techniques.	interval, in our study it is 15 to 25 meter. Since UWB is based on carrier less transmission so UWB equipment are less complex than carrier based transmission, so we can settle for short range with extremely high data rate communication
16. UWB system and method for smart public transport system	Chawla, R., Dhakate, M., & Chaurasia, S. (2020, February). System and Method for Smart Public Transportation System. In 2020 International Conference on Industry 4.0 Technology (I4Tech) (pp. 51-54). IEEE.	With the increase in population, rapid explode in rate of vehicles has resulted in an overload on traffic management. Public transportation, being a pivotal role, is the most affordable means of transportation. The major impediment of traveling with bus is the inconsistent arrival time which may be due to unforeseen circumstances. Even though bus schedule is known, there are a number of reasons that bus may not arrive as expected.	Traffic congestion, heavy downpour, bus breakdown, accident and day-to-day problems faced by bus company can delay or completely interrupt bus service. Another drawback of the primitive bus system is that the safety of passengers has never been considered. The current system has always been ignorant towards specially able people. Thus, all the shortcomings have given the intuition of developing an IoT enabled system that will inform the travellers prior about the bus arrival time, facilitating passengers to plan trips with minimum wait-time. This is done by making use of Bluetooth Low Energy (BLE) UWB (Ultra Wide Band) beacons to notify the commuters about arriving bus at the bus stop. The proposed system would take into consideration the needs of specially-abled

			people and offer service that will help improve their overall traveling experience.
17. UWB locating algorithms	Shen, C., Wang, C., Zhang, K., Wang, X., & Liu, J. (2019). A time difference of arrival/angle of arrival fusion algorithm with steepest descent algorithm for indoor non-line-of-sight locationing. International Journal of Distributed Sensor Networks, 15(9), 1550147719860354.	In complex indoor propagation environment, the non-line-of-sight error caused by various obstacles brings great error to node positioning. Choosing the appropriate signal transmission methods is important to improve node indoor positioning accuracy. In this research, ultra-wideband technology, as baseband with high theoretical positioning accuracy and real-time performance, is implemented to transmit indoor signals.	The proposed fusion algorithm with ultra-wideband baseband takes advantages from both time difference of arrival and angle of arrival algorithms, combined through the steepest descent algorithm. The non-line-of-sight signal estimation error is iteratively eliminated to achieve effective positioning accuracy. The experimental results indicate that the novel time difference of arrival/angle of arrival fusion algorithm with steepest descent algorithm can largely improve node positioning accuracy and stability.
18. UWB general introductions	Nikookar, H., & Prasad, R. (2008). Introduction to ultra wideband for wireless communications. Springer Science & Business Media.	Compared to traditional carrier-based, Ultra-Wide Band (UWB), or carrier-less, systems implement new paradigms in terms of signal generation and reception. Thus, designing an UWB communication system requires the understanding of how excess bandwidth and very low transmitted powers can be used jointly to provide a reliable radio link. UWB offers systems transceiver potential for very simple implementations.	Comparison between UWB and traditional narrow-band systems highlights the following features: - Large bandwidth enables very fine time-space resolution for accurate location of the UWB nodes and for distributing network time stamps. - Very short pulses are effectively counter-fighting the channel effect in very dense multipath environments. - Data rate (number of pulses transmitted per bit) can be traded with power emission control and distance coverage. - Very low power density leads to low probability of signal detection and

			adds security for all the layers of the communication stack. Very low power density is obtained through radio regulation emission masks; UWB systems are suitable for coexistence with already deployed narrow-band systems
19. UWB survey papers	Niemelä, V., Haapola, J., Hämäläinen, M., & Iinatti, J. (2016). An ultra wideband survey: Global regulations and impulse radio research based on standards. IEEE Communications Surveys & Tutorials, 19(2), 874-890.	This paper presents an updated survey on research related to ultra wideband (UWB) communications, particularly that of impulse radio (IR) technology. In addition to the research, we survey UWB physical layer specifications of the two existing standards—the IEEE 802.15.6-2012 and the IEEE 802.15.4-2015—as well as the leading global UWB spectrum regulatory limitations which have been updated recently.	The latter standard including the UWB specifications was first published in 2007 and the latest revision dates to 2015. The focus in this paper is the period from 2007 to 2015. Our purpose is to provide an in-depth survey with a clearly specified topic together with the standard specifications and the related regulatory restrictions. Additionally, the last part of this paper discusses the possibilities of increasing the current IR-UWB data rates to meet increasing future demands.
20. UWB hybrid RFID real-time locating system for IoT	Zhai, C., Zou, Z., Zhou, Q., Mao, J., Chen, Q., Tenhunen, H., ... & Xu, L. (2017). A 2.4-GHz ISM RF and UWB hybrid RFID real-time locating system for industrial enterprise Internet of Things. Enterprise Information Systems, 11(6), 909-926.	This paper presents a 2.4-GHz radio frequency (RF) and ultra-wide bandwidth (UWB) hybrid real-time locating system (RTLS) for industrial enterprise Internet of Things (IoT). It employs asymmetric wireless link, that is, UWB radio is utilised for accurate positioning up to 10 cm in critical sites, whereas 2.4-GHz RF is used for tag control and coarse positioning in non-critical sites. The specified communication protocol and the adaptive tag synchronisation rate ensure reliable and deterministic access with a scalable system capacity and avoid	The tag, consisting of a commercial 2.4-GHz transceiver and a customised application-specific integrated circuit (ASIC) UWB transmitter (Tx), is able to achieve up to 3 years' battery life at 1600 tags per position update second with 1000 mAh battery in one cluster. The time difference of arrival (TDoA)–based positioning experiment at UWB radio is performed on the designed software-defined radio (SDR) platform.

		unpredictable latency and additional energy consumption of retransmissions due to collisions.	
21. UWB general overview	Di Benedetto, M. G. (Ed.). (2006). UWB communication systems: a comprehensive overview.	Ultrawideband (UWB) communication systems offer an unprecedented opportunity to impact the future communication world. The enormous available bandwidth, the wide scope of the data rate / range trade-off, as well as the potential for very low-cost operation leading to pervasive usage, all present a unique opportunity for UWB systems to impact the way people and intelligent machines communicate and interact with their environment.	The aim of this book is to provide an overview of the state of the art of UWB systems from theory to applications. Due to the rapid progress of multidisciplinary UWB research, such an overview can only be achieved by combining the areas of expertise of several scientists in the field. More than 30 leading UWB researchers and practitioners have contributed to this book covering the major topics relevant to UWB. These topics include UWB signal processing, UWB channel measurement and modelling, higher-layer protocol issues, spatial aspects of UWB signalling, UWB regulation and standardization, implementation issues, and UWB applications as well as positioning. The book is targeted at advanced academic researchers, wireless designers, and graduate students wishing to greatly enhance their knowledge of all aspects of UWB systems.
22. UWB peak detection for WSN and IoT applications	Sharma, S., Gupta, A., & Bhatia, V. (2017, June). A simple modified peak detection based UWB receiver for WSN and IoT applications. In 2017 IEEE 85th Vehicular Technology Conference (VTC Spring) (pp. 1-6). IEEE.	Ultra-wide band (UWB) communication is a viable solution for Wireless Sensor Network (WSN) and Internet of Things (IoT) due to low cost and low power requirement. However, UWB transceiver design is more complex due to large bandwidth and precise synchronization requirement. In this paper,	The proposed receiver divides each data symbol frame duration into smaller multiple time windows. In each time window, peak of received signal is detected independently using threshold comparison. The transmitted signal is detected in a frame by employing decisions on all multiple time windows. From

		we propose a simple peak detection based non-coherent UWB receiver, suitable for low data rate WSN and IoT based applications.	simulation, it is observed that the proposed receiver outperforms existing non-coherent receivers. The performance analysis of the proposed receiver is carried out by using time hopping pulse position modulation (TH-PPM) UWB signal in additive white Gaussian noise (AWGN), multipath communication using the existing IEEE 802.15.4a standard.
23. UWB positioning using virtual anchors	Meissner, P., Gigl, T., & Witrisal, K. (2010, September). UWB sequential Monte Carlo positioning using virtual anchors. In 2010 International Conference on Indoor Positioning and Indoor Navigation (pp. 1-10). IEEE.	We present a novel UWB indoor localization concept that performs the position estimation with a set of virtual anchor nodes, generated from a single physical anchor and floor plan information. Using range estimates to the virtual anchors, we perform multilateration to estimate the position of an agent. Previous work has shown the general applicability of this concept. In this contribution, we use a moving agent to exploit the correlation in successive positions using state-space concepts. A motion model for the agent and the measurement likelihood function allow for the use of the powerful framework of Bayesian state estimation. With this concept, we can propagate prior information on the agent position from one time step to the next.	The statistical model for the ranging to the virtual anchor's accounts for several imperfections, which lead to multimodal and heavy-tailed measurement distributions. We show how modified versions of the Kalman filter as well as a particle filter can account for these imperfections and yield accurate and robust position estimates. In a typical indoor pedestrian motion scenario, we can achieve an accuracy of about 45 cm for 90% of the estimates.
24. UWB propagation channels	Molisch, A. F. (2009). Ultra-wide-band propagation channels. Proceedings of the IEEE, 97(2), 353-371.	Understanding ultra-wide-band (UWB) propagation channels is a prerequisite for UWB system design as well as communication-theoretic and information-	If the absolute bandwidth is large, the shape of the impulse responses as well as the fading statistics change. This paper also describes methods for measuring UWB

		theoretic investigations. This paper surveys the fundamental properties of UWB channels, pointing out the differences to conventional channels. If the relative bandwidth is large, the propagation processes, and therefore path loss and shadowing, become frequency-dependent, and the well-known wide-sense stationary uncorrelated scattering model is not applicable anymore.	channels and extracting channel parameters. Throughout this paper, the relationship between channel properties and other areas of UWB research are pointed out.
25. UWB based non-line-of-sight identification in harsh environments	Silva, B., & Hancke, G. P. (2016). IR-UWB-based non-line-of-sight identification in harsh environments: Principles and challenges. IEEE Transactions on Industrial Informatics, 12(3), 1188-1195.	Impulse radio ultrawideband ranging has recently received significant attention due to the high accuracy it can achieve. Although most research efforts have focused on ranging in indoor and outdoor environments, other environments such as harsh industrial environments introduce unique challenges. This paper discusses the impact of propagation characteristics of harsh industrial environments on ranging accuracy, and also discusses principles and challenges of non-line-of-sight identification in industrial scenarios.	To illustrate these challenges, a measurement campaign using 802.15.4a radios was conducted in a Heavy Machines Laboratory. The results show that the non-line-of-sight condition can be accurately identified if adequate models for such an environment are used.
26. UWB monopole antenna for automotive communications	Alsath, M. G. N., & Kanagasabai, M. (2015). Compact UWB monopole antenna for automotive communications. IEEE Transactions on Antennas and Propagation, 63(9), 4204-4208.	This communication presents a bandwidth-enhanced, compact, monopole antenna with modified ground plane for modern automotive ultra wide-band (UWB) applications. The proposed antenna has hybrid geometry and is constructed using half circular ring and half square ring. The ground plane of the fundamental radiator is	The designed antenna covers 3.1–10.9 GHz frequency spectrum with VSWR≤2 . This antenna can be conveniently placed inside the shark fin housing or it can be printed along with the existing print circuit board (PCB) electronics nullifying the need for dedicated location for in-car communications. Furthermore, a simple

		curved and defected to improve the VSWR bandwidth. An extended ground stub is added to further enhance the bandwidth to suit the modern automotive requirements.	two-port multiple input multiple output (MIMO) antenna is constructed and its diversity performance is estimated. The prototype is fabricated and tested for impedance and radiation characteristics.
27. UWB localization of semi-autonomous floor scrubber	Čelan, V., Stančić, I., & Musić, J. (2017). Ultra wideband assisted localization of semi-autonomous floor scrubber. Journal of Communications Software and Systems, 13(2), 109-119.	The paper describes the design and features of the novel semi-autonomous floor scrubber add-on module, used for cleaning large indoor spaces. Module is designed in such a manner that it can be easily attached and detached from scrubber machine and that additional sensors can be introduced if needed. The paper focuses on the localization capabilities of the machine in several sensor setups with emphasis on the use of ultra wideband (UWB) real-time localization system (RTLS). It also proposes fusion of sensor data from several sources including novel use of wheel encoder's data in UWB setup.	Analysis is performed in terms of localization accuracy and reliability as well as associated advantages and disadvantages. Obtained results demonstrated that inclusion of UWB subsystem, despite its price and accuracy (20 cm in ideal, line of sight, conditions), based on behaviour switching yields more reliable and accurate results in open spaces (up to 25 times in position and 2 times in orientation) and that its accuracy can be further improved with inclusion of wheel encoder data.
28. UWB applications in public transport	Skrebtsov, A., Burnic, A., Xu, D., Waadt, A., & Jung, P. (2011, March). UWB applications in public transport. In 2011 International Conference on Communications, Computing and Control Applications (CCCA) (pp. 1-4). IEEE.	Wireless connectivity will become an integral component of the aircraft cabin in the near future. For the planning of the reliable network a detail analysis of the coverage is required. This paper observes the coverage in an aircraft cabin for an OFDM UWB system based on the ECMA-368 standard. For this purpose, based on real measurement in an airplane cabin mock-up, a Saleh-Valenzuela channel model and a path-loss model are presented. These	Implementation of wireless technology for the in-cabin connection allows achieving higher cabin layout flexibility, design costs and overall weight reduction. Moreover, new generation services, like high-definition video or high-speed internet access can provided to the passengers. To improve the flexibility and simplicity of future cabin layouts at a sustained high safety, security and reliability of the communication services, improved protocol and network

		models are used to obtain the block error rates and the throughput in an in-cabin environment. In the near future, radio communications will be deployed in aircraft for cabin management functions, intra crew communications and logistics tasks as well as safety, security and entertainment tasks. Nowadays, GSM (Global System for Mobile Communications) and W-LAN (Wireless Local Area Network) networks are already deployed for passenger services.	architectures are required. One of the first candidates is ultra-wideband (UWB) radio.
29. UWB technology for smart cities IoT applications	Minoli, D., & Occhiogrosso, B. (2018, September). Ultrawideband (UWB) technology for smart cities IoT applications. In 2018 IEEE international smart cities conference (ISC2) (pp. 1-8). IEEE.	Ultrawideband (UWB) technology provides relatively high throughput at short distances by utilizing low-power pulse transmission as a coexisting radio service in the C/X-band portion of the electromagnetic spectrum. This paper aims at validating the suitability of UWB technology for emerging Internet of Things (IoT) applications.	The expectation in the industry is that e-health applications that entail Body Area Networks, Smart City applications dealing with autonomous vehicles and precise location, Positive Train Control in the context of rail transportation, and other near field communications will become prevalent in the near future. This review article provides a description of UWB technology in the IoT environment, as well assessing its technical limitations.
30. UWB localization algorithm exploiting knowledge of the service	Arias-de-Reyna, E., & Mengali, U. (2013). A maximum likelihood UWB localization algorithm exploiting knowledge of the service area layout. Wireless personal communications, 69(4), 1413-1426.	In this paper a method for ultra-wideband (UWB) localization for indoor applications is proposed. Beacons at known locations exchange signals with a tag to the purpose of estimating its position from range measurements. These measurements are accurate only when the ray corresponding to the direct path (DP) from tag to beacon is strong enough.	In an UWB indoor environment, however, the DP may be blocked by thick walls or metallic obstacles, giving rise to large range errors. Several methods are available to mitigate this problem, exploiting different degrees of prior information. Techniques exploiting range error models or based on traditional fingerprinting lead to better results than methods that do not require any

area layout			prior knowledge. We propose a new method that combines the maximum likelihood principle with range error models and special fingerprints. Its performance, assessed by simulation and compared to other techniques, is shown to be superior to traditional fingerprinting in the presence of environmental changes.
31. UWB localization system for indoor robot navigation	Krishnan, S., Sharma, P., Guoping, Z., & Woon, O. H. (2007, September). A UWB based localization system for indoor robot navigation. In 2007 IEEE International Conference on Ultra-Wideband (pp. 77-82). IEEE.	For robots to become more popular for domestic applications, the short comings of current indoor navigation technologies have to be overcome. In this paper, we propose the use of UWB-IR for indoor robot navigation. Various parts of an actual implementation of a UWB-IR based robot navigation system such as system architecture, RF sub-system design, antennas and localization algorithms are discussed.	It is shown that by properly addressing the various issues, a localization error of less than 25 cm can be achieved at all points within a realistic indoor localization space.
32. UWB modulation and multiple access	Cui, S. (2011). Modulation and multiple access techniques for ultra-wideband communication systems. Cleveland State University.	Two new energy detection (ED) Ultra-Wideband (UWB) systems are proposed in this dissertation. The first one is an ED UWB system based on pulse width modulation (PWM). The bit error rate (BER) performance of this ED PWM system is slightly worse than ED pulse position modulation (PPM) system in additive white Gaussian noise (AWGN) channels.	When a GFSK system is compared to a PWM system, it will always achieve approximately 2 dB improvement in AWGN channels, multipath channels, and in the presence synchronization errors. However, a PWM system uses lower-order derivatives of the Gaussian pulse to transmit signal, and this leads to a simple pulse generator. In this dissertation, an optimal threshold is applied to improve PPM system performance. The research results show that the application of an optimal threshold can effectively mitigate

			the effect of CMI and synchronization errors and achieve performance improvement. Finally, the multiple access schemes are discussed, and time hopping is chosen as the multiple access scheme for PWM and GFSK systems.
33. UWB indoor positioning	Alarifi, A., Al-Salman, A., Alsaleh, M., Alnafessah, A., Al-Hadhrami, S., Al-Ammar, M. A., & Al-Khalifa, H. S. (2016). Ultra wideband indoor positioning technologies: Analysis and recent advances. Sensors, 16(5), 707.	In recent years, indoor positioning has emerged as a critical function in many end-user applications, including military, civilian, disaster relief and peacekeeping missions. In comparison with outdoor environments, sensing location information in indoor environments requires a higher precision and is a more challenging task in part because various objects reflect and disperse signals.	Ultra-Wide Band (UWB) is an emerging technology in the field of indoor positioning that has shown better performance compared to others. While SWOT is not a quantitative approach, it helps in assessing the real status and in revealing the potential of UWB positioning to effectively address the indoor positioning problem. Unlike previous studies, this paper presents new taxonomies, reviews some major recent advances, and argues for further exploration by the research community of this challenging problem space.
34. UWB general review	McKeown, D., & Siwiak, K. (2005). Ultra-wideband radio technology. John Wiley & Sons.	Ultra-wideband (UWB) has been among the most controversial technologies of modern times. Its applications seem endless, its capabilities miraculous and yet it is so poorly understood. In this volume, the authors combine talents to de-mystify ultra-wideband radio and explain it in language that is accessible to non-technologists as well as technologists. They contrast UWB with conventional radio technology so that fundamental, technically accurate information devoid of specific technical and analytical details is accessible for marketing managers, business developers, engineering	Discusses the applications of UWB in terms of the unique properties and advantages of UWB Provides simple high level, conceptual discussions of UWB followed with more detailed, scientific, mathematical, engineering focused explanations Presents a global perspective by tracing UWB throughout the history of radio, providing a modern basis for the re-

		managers, technology managers, potential investors, financial analysts, executive recruiters, technical writers, and technologists from other fields. The authors also include enough specific technical and engineering information about UWB, for the seasoned technologists, engineers, scientists and academicians who need to understand the topic at an entry level.	emergence of the technology and for the current regulatory and standards activities Features insights into the reasons why the technology developed the way it did Explains the key advantages of UWB, including its bandwidth, potential simplicity and huge system capacity
35. UWB applications in public transport	Bovelli, S., Leipold, F., & Fischer, W. (2009, March). Applications of high and low data rate UWB technology in public transportation. In 2009 6th Workshop on Positioning, Navigation and Communication (pp. 283-284). IEEE.	This abstract describes a series of possible applications of the ultra-wide band wireless technology in public transportation environment. Application scenarios for both the high data rate technology based on WiMedia and the low data rate technology based on impulse radio are presented, indicating the specific advantages provided by UWB in comparison to other narrow band wireless standards.	The work is performed in the EUWB ICT project to enable the introduction of the UWB wireless communication for the described application and is encompassed with a UWB demonstrator that is finally described.
36. Indoor Positioning for disability	Mirza, R., Tehseen, A., & Kumar, A. J. (2012, March). An indoor navigation approach to aid the physically disabled people. In 2012 International Conference on Computing, Electronics and Electrical Technologies (ICCEET) (pp. 979-983). IEEE.	Physical disability becomes a major obstacle in the lives of physically challenged people and they are deprived of performing even their day-to-day activities without anybody's aid. One of the common problems they face is navigating their own home. So we proposed a system which aids such people to navigate their home or any indoor environment with all ease. Using this system not only can they reach any desired room in their home, but they could also reach to the	We provide an obstacle avoidance technique suitable for this type of navigation which detects dynamic obstacles present in the real time environment. This proposed system can be of immense use to various physically disabled people and thus making their lives easy without any external aid.

		commonly used places inside a room such as sofa, television, refrigerator, or any such commonly used places using voice commands.	
37. UWB indoor positioning	Zhang, K., Shen, C., Gao, Q., Zheng, L., Wang, H., & Li, Z. (2018). Precise positioning system of ship interior based on UWB ultra wideband technology. Journal of Coastal Research, (83 (10083)), 908-912.	A new ship indoor accurate positioning system was proposed. Firstly, the UWB ship indoor positioning system of power module, MCU module, UWB module and chip selection of memory module were given.	The hardware design of system label / micro base station was completed. Then, based on the UWB localization algorithm, the time difference of arrival (TDOA) improved algorithm using reference tags auxiliary information was proposed. The software design process of system label / micro base station was completed. Experimental result shows that this system has high positioning accuracy. and the low time delay of receipt signal.
38. Infrared sensors indoor positioning	Sikdar, A., Zheng, Y. F., & Xuan, D. (2015, May). An iterative clustering algorithm for classification of object motion direction using infrared sensor array. In 2015 IEEE International Conference on Technologies for Practical Robot Applications (TePRA) (pp. 1-6). IEEE.	Infrared sensors have been widely used in the field of robotics. This is primarily because these low cost and low power devices have a fast response rate that enhances realtime robotic systems. However, the use of these sensors in this field has been largely limited to proximity estimation and obstacle avoidance. In this paper, we attempt to extend the use of these sensors from just distance measurement to classification of direction of motion of a moving object or person in front of these sensors.	A platform fitted with 3 infrared sensors is used to record distance measures at intervals of 100ms. A histogram based iterative clustering algorithm segments data into clusters, from which extracted features are fed to a classification algorithm to classify the motion direction. Experimental results validate the theory that these low cost infrared sensors can be successfully used to classify motion direction of a person in real time.
39. Indoor positioning survey	Song, Z., Jiang, G., & Huang, C. (2011, May). A survey on indoor positioning technologies. In International conference on theoretical and mathematical foundations of computer	This paper investigates some key technologies and algorithms of indoor positioning and analyses their advantages and disadvantages in the terms of the	Location-aware service is one of the most important parts of the internet of things. And how to obtain the location information is the key point of location-aware service.

	science (pp. 198-206). Springer, Berlin, Heidelberg.	positioning range, accuracy, and cost. Finally, some issues need to be resolved in future are discussed.	
40. Indoor positioning general review	Svalastog, M. S. (2007). Indoor positioning-technologies, services and architectures (Master's thesis).	This thesis is about Location Based Computing Systems (LBCS), with emphasis on their underlying positioning systems. The first part of the thesis introduces a three-layered reference model for discussing LBCS and gives background information on positioning systems in general—components, designs, properties, and techniques. It also includes an overview of existing systems for indoor positioning. The second part of the thesis introduces a case study, which consists of two parts. One is an in-depth overview of a specific Location Based Service (LBS) called a mobile electronic tour guide, a service typically implemented on hand-held devices which are given to visitors at different exhibitions as a means for enhancing their experience of it.	With distributed and pervasive intelligence, ITSp clearly impose some stringent requirements on the information exchange among all entities within the ITSp, in terms of the information availability, reliability, fidelity, and timeliness. These requirements, together with the high mobility of vehicles and the highly variable network topology, make the communications and networking for ITSp very challenging. This article will introduce the concept of ITSp and analyse possible communication technology candidates for ITSp. Further discussions will also be provided at the end of this article.
41. Indoor positioning general review	Al-Ammar, M. A., Alhadhrami, S., Al-Salman, A., Alarifi, A., Al-Khalifa, H. S., Alnafessah, A., & Alsaleh, M. (2014, October). Comparative survey of indoor positioning technologies, techniques, and algorithms. In 2014 International Conference on Cyberworlds (pp. 245-252). IEEE.	The user location information represents a core dimension as understanding user context is a prerequisite for providing human-centered services that generally improve quality of life. In comparison with outdoor environments, sensing location information in indoor environments requires a higher precision and is a more challenging task due in part to the expected various	Unlike previous studies and surveys, our survey present new taxonomies, review some major recent advances, and argue on the area open problems and future potential. We believe this paper would spur further exploration by the research community of this challenging problem space.

		objects (such as walls and people) that reflect and disperse signals. In this paper, we survey the related work in the field of indoor positioning by providing a comparative analysis of the state-of-the-art technologies, techniques, and algorithms.	

Biometrics

Biometrics is an area that is well researched. The literature is for a large part focused on performance measures, for instance, given the recent appearance of masks in public transport, research has been focused on face recognition while wearing masks. Literature also focuses on the evaluation of advanced biometrics information such as iris, voice and vein recognition which have been introduced for more secure identification purpose.

Quite a large number of publications focus on biometrics in transport use case. Technically, this technology is one of the more mature use cases. Please see our regulatory review report, that high lights the more sensitive ethical and regulatory issues surrounding the use of biometrics in public transport.

More research is required in for user acceptance, fair evasion control and performance in very crowded, unstructured areas.

Biometrics: Evaluation criteria

Table 3. Key evaluation requirements- Biometrics (facial recognition)

Key requirements	
Technology readiness – now vs. emerging	Facial recognition: commercially available, and used by major operator [1]
Certainty/reliability (e.g., interference)	High-level certainty and reliability without microwave and radiation interference affect
Accurate/very low error rates	Facial recognition: 861.Ideally 99.97% [2] available with face mask. 132 out of 275 vendors has less than 0.8% error rate. [3]
Secure– not easy to forge, clone	The possibility to clone or forge people's face information is as low as 0.[3]

Use case requirements (Facial recognition)	
Identification	**Facial recognition**: Artificial Intelligence and facial recognition algorithms with a state-of-the-art optical set combining 2D, 3D, and infra-red cameras (infra-red cameras can capture image even in a dark environment) [4,5]

Tokenisation /Authentication	Facial recognition stores images on a secure server and communication is encrypted using SSL to avoid attacks or traffic sniffing [6]
Positioning & trip definition: Registration in (begin of ticket) Registration out (end of ticket) Repeat for next leg of trip	Track passenger's position via back-end middleware using biometric scanner position and check-in/check-out timestamp [7]
Capacity to process multiple entries simultaneously (large quantities / high throughput) – unless separate lane	To be confirmed: Facial recognition: Multiple faces can be scanned simultaneously. (Around 20 people). It supports high throughput passengers.[7]
Can detect entry in vehicle (as opposed to walking by). Determines with high accuracy which mode of transport has been/is being used	Can detect the entry for train station via fixed facial recognition devices. On bus/ taxi/ tram, portable facial recognition devices may be required to detect the entry of vehicle In the future, apps on mobile phone supporting facial recognition will be promising to simplify the check-in.
Execute gate open and close 'just in in time' for gated solutions Consider gated and non-gated – in a variety of use cases: bus, train, tram, ferry, taxi, on demand	Gate will open and close automatically when authentication process is completed in train station. China introduced biometric facial recognition tech on train and railway station in Beijing Railway station.[1] Portable biometrics devices may be required on bus/taxi/tram. To install biometrics devices on each bus/taxi/tram stop will increase the cost.
Works indoor and outdoor (with and without GPS)	Yes, works indoor and outdoor
Cover fixed and variable routes, i.e., cannot rely on fixed infrastructure. Work in taxi's, minibuses, mopeds, bike sharing, etc.	More research required
High feasibility of installation across all use cases	No, most use cases focus on gate management
Low maintenance/Asset Management System (also Resistant to vandalism)	More research required

Risks/concerns?	- Adoption/Privacy issues - High demands on security - Installation cost

Table 4. Key evaluation requirements- Biometrics (others)

Key requirement	
Technology readiness – now vs. emerging	**Voice recognition**: Proven in 1. Web based applications, 2. Interactive Voice Response based banking and health systems. 3.Audio signatures for digital documents.[8] **Fingerprint**: Mature technology proven in access control system and border management. [8] **Vein recognition:** Palm vein authentication is a vein feature authentication biometric technology. Mature technology proven in banking, access control, hospital identification. [8] Commercial products not available for public transport
Certainty/reliability (e.g., interference)	High level certainty and reliability without the interference from communication radios.
Accurate/very low error rates	**Voice recognition**: Google boasted a 95% word accuracy rate for U.S. English, the highest out of all the voice-assistants currently out there.[9] FAR (False acceptance rate) is 2% and FRR (False rejection rate) is 10%.[8] **Fingerprint**: The best system was accurate 98.6 percent of the time on single-finger tests, 99.6 percent of the time on two-finger tests, and 99.9 percent of the time for tests involving four or more fingers. These accuracies were obtained for a false positive rate of 0.01 percent [10]. FAR is 2% and FRR is 2%. [8] **Vein recognition**: Vein recognition had a false acceptance rate of less than 0.00008% and a false rejection rate of 0.01% [8,11]
Secure– not easy to forge, clone	This depends on the deployment, but it can be highly secure.[8]

Use case requirements	**Tech solution**
Identification	Fingerprint: Verifies 4 fingerprints in less than 1 second, through a fully touchless hand wave gesture.[12] Voice recognition: the voice biometric system captures a new speech sample, creates a template from the sample, and compares it against the enrolment template.[8] Vein recognition: Vein recognition, known as vascular biometrics, refers to technology that measures parts of a subject's circulatory system which is as unique as a fingerprint. High resolution cameras using infrared or near infrared light are used to acquire the pattern of the vein.[8]

Tokenisation /Authentication	**Fingerprint**: A privacy-compliant fingerprint recognition system based on homomorphic encryption that may connect to access control system on cloud or local server [13] **Voice recognition**: Can be analysed and encrypted by applying algorithm on network server for tokenisation and authentication process. [14] **Vein recognition:** Can be captured and analysed by handheld vein reader and pass the tokenisation and authentication process
Positioning & trip definition: Registration in (begin of ticket) Registration out (end of ticket) Repeat for next leg of trip	1.Track passenger's position and each stop of the trips via biometric scanner position and check-in/check-out timestamp. 2. Voice Alert System that can navigate disability people location and help them take the bus.[15]
Capacity to process multiple entries simultaneously (large quantities / high throughput) – unless separate lane	Voice/Fingerprint/Vein recognition: only one person's voice/fingerprint/vein is detected at one time.
Can detect entry in vehicle (as opposed to walking by). Determines with high accuracy which mode of transport has been/is being used	It will be practical in the near future to detect the entry for train station / bus entry / tram entry if the biometrics devices scan the passengers' biometrics information when they get on/off.
Execute gate open and close 'just in in time' for gated solutions Consider gated and non-gated – in a variety of use cases: bus, train, tram, ferry, taxi, on demand	Gate will open and close automatically when authentication process is completed in the train station. Handheld biometrics devices will be required for passengers to check in and check out on taxi, bus, and tram. Apps on mobile phone supporting biometrics authentications will be very promising in the future.
Works indoor and outdoor (with and without GPS)	Yes, works indoor and outdoor. No dependency of GPS location.
Cover fixed and variable routes, i.e., cannot rely on fixed infrastructure. Work in taxi's, mini buses, mopeds, bike sharing, etc.	More research required
High feasibility of installation across all use cases	Better than facial, but requires console in each vehicle
Low maintenance/Asset Management System (also Resistant to vandalism)	More research required

Risks/concerns?	- Privacy and regulatory issue - Installation cost

Biometrics: Literature overview

Tech Type	Reference	Summary	Key Point of Interest
1. Biometric - Facial Recognition	Pascu, L. (2020). Face biometrics deployed for train station security in Asia, Germans pushback on public surveillance. Retrieved 2022, from https://www.biometricupdate.com/202001/face-biometrics-deployed-for-train-station-security-in-asia-germans-pushback-on-public-surveillance	The current status of face biometrics deployed for train station security in Asia and Germans pushback on public surveillance	-China introduces biometric facial -recognition tech on train, railway station -India installs facial recognition at train station -Germans refuse automatic facial recognition in public places
2. Biometric - Facial Recognition	CSIS. (2020). How Accurate are Facial Recognition Systems – and Why Does It Matter? Retrieved 2022, from https://www.csis.org/blogs/technology-policy-blog/how-accurate-are-facial-recognition-systems-%E2%80%93-and-why-does-it-matter	Introduce the facial recognition, the principle, the accuracy, and risk management.	In ideal conditions, facial recognition systems can have near-perfect accuracy. Verification algorithms used to match subjects to clear reference images (like a passport photo or mugshot) can achieve accuracy scores as high as 99.97% on standard assessments like NIST's Facial Recognition Vendor Test (FRVT).This is comparable to the best results of iris scanners.
3. Biometric - Facial Recognition	Lewis, J. A., & Crumpler, W. (2021). Questions about Facial Recognition. Washington, D.C., United States.	We reviewed the most salient of these concerns for accuracy and for their implications for policymaking, and came to several conclusions. Risk from the use of facial recognition technology is best managed by implementing rules and safeguards appropriate for each case. We must be careful to ensure that any new rules are not based on information that is incorrect or outdated. Technological change is not going to stop and the use of artificial intelligence in applications like facial recognition will continue to grow. We do not want to continue the precedent of allowing unregulated use of technology—the	First conclusion is that to reduce concerns about facial recognition, Congress needs to pass effective privacy legislation to govern digital technologies. Facial recognition requires access to personally identifiable information (PII). A second conclusion is that improvements in facial recognition technology, especially in how algorithms are developed and trained, will continue to reduce the risks of error and bias.

		internet's effects on privacy and security show the risk of a laissez faire approach—but we also want to avoid overregulation, since this is a proven way to stop innovation and give technological advantage to other countries.	
4. Biometric - Facial Recognition	IDEMIA. (2021). Idemia Visionpass Facial Recognition. Retrieved 2022, from https://www.aranasecurity.com/products/idemia-visionpass-face-recognition/	Introduce IDEMIA's VisionPass facial recognition access control device.	In this product, IDEMIA associated its latest advances in Artificial Intelligence and facial recognition algorithms with a state-of-the-art optical set combining 2D, 3D and infra-red cameras in order to meet the expectations of the most demanding clients.
5. Biometric - Facial Recognition	Ghiass, R. S., Arandjelovic, O., Bendada, H., & Maldague, X. (2013). Infrared Face Recognition: A Literature Review. International Joint Conference on Neural Networks.	Automatic face recognition (AFR) is an area with immense practical potential which includes a wide range of commercial and law enforcement applications, and it continues to be one of the most active research areas of computer vision. Even after over three decades of intense research, the state-of-the-art in AFR continues to improve, benefiting from advances in a range of different fields including image processing, pattern recognition, computer graphics and physiology.	Systems based on visible spectrum images continue to face challenges in the presence of illumination, pose and expression changes, as well as facial disguises, all of which can significantly decrease their accuracy. Amongst various approaches which have been proposed in an attempt to overcome these limitations, the use of infrared (IR) imaging has emerged as a particularly promising research direction. This paper presents a comprehensive and timely review of the literature on this subject.
6. Biometric - Facial Recognition	SolidPass. (2021). Facial Recognition, Authentication and Mobile Security Token. Retrieved 2022, from http://www.solidpass.com/authentication-methods/facial-recognition-authentication.html	Introduce Facial Recognition, Authentication and Mobile Security Token. SolidPass supports facial recognition as an added layer of authentication and security. Facial recognition is a form of biometric authentication. SolidPass harnesses the advanced	OATH Compliant Time-synchronized Tokens As a member of the Initiative for Open Authentication, SolidPass tokens are built OATH compliant. SolidPass uses the standards-based strong two-factor

		camera capabilities of the latest smartphones to perform facial recognition.	authentication HOTP algorithm endorsed by OATH, providing compatibility with third-party software. Easy integration of SolidPass into existing IT back-ends and support of various architectures. The authentication server is OS independent and supports Linux (tested on most distributions like Redhat, Ubuntu and Novell Suse), Microsoft Windows Server (NT, 2003, XP), Sun Solaris and all operating systems that support enterprise Java.
7. Biometric – General review	Thales Group. (2021). New ABC eGates: smaller footprint, modular design and faster passenger processing. Retrieved 2022, from https://www.thalesgroup.com/en/markets/digital-identity-and-security/government/eborder/egates	The new Thales Gemalto ABC eGates combine expertise in document verification, passenger biometric authentication with an optimized and modular hardware solution to automate border control. They provide greater flexibility with regards to the airport floor and passenger flow management and process passengers faster. Now you can deliver a smoother passenger journey and facilitate entry and exit management.	Automation of the border control process with state-of-the-art passenger authentication software leveraging biometric data contained in the ePassport and captured live at the gate, Reduced waiting times and passengers carrying out the checks themselves in just a few seconds, allowing for greater empowerment and more dwell time in a duty-free area, Flexibility in terms of hardware design and process management for the benefit of both airports and border authorities.
8. Biometric – General review	T.Sabhanayagam, Venkatesan, D. V., & Senthamaraikannan, D. K. (2018). A Comprehensive Survey on Various Biometric Systems. International	This paper presents an overview to various biometric systems, their applications, limitations and the different type of biometrics recognition systems.	The current research trends have shown the prospect of using Brain waves and ECG as biometric identification. The current research indicates that the

	Journal of Applied Engineering Research, 13(5), 2276-2297.		identification of human is more effective and far more challenging. Various journal and international conferences research papers have been studied and summarize the progress in the direction of cost-effective and an innovative manner.
9. Biometric - Speech Recognition	Summa Linguae. (2021). A Complete Guide to Speech Recognition Technology. Retrieved 2022, from https://summalinguae.com/language-technology/guide-to-speech-recognition-technology/	History of Speech Recognition Technology How Does Voice Recognition Work? How do companies build speech recognition technology? How Voice Assistants Bring Speech Recognition into Everyday Life Where else is speech recognition technology prevalent? Speech Recognition Technology: The Focus Moving Forward Collect Better Data	Here are a few key areas 1. Mobile app voice integration Integrating voice-tech into mobile apps has become a hot trend and will remain so because speech is a natural user interface (NUI). 2. Individualized experiences Voice assistants will also continue to offer more individualized experiences as they get better at differentiating between voices. 3. Smart displays
10. Biometric – Fingerprint Recognition	Thakkar, D. (2021). How Accurate are today's Fingerprint Scanners? Limitations, Errors and Their Effect on the Accuracy. Retrieved 2022, from https://www.bayometric.com/how-accurate-are-todays-fingerprint-scanners/	Performance and security offered by today's fingerprint scanners are highly depended on their matching accuracy and ability to keep errors under control. If fingerprint recognition devices fail to maintain optimum matching accuracy and error control mechanism, they will become more of a problem than a solution.	The study clearly shows that today's fingerprint scanners have reached a point where their accuracy can be more than 99 percent, provided you use high-quality scanners.
11. Biometric – Vein Recognition	Fujitsu. (2021). Palm Vein Pattern Authentication Technology. Tokyo Japan.	This paper introduces palm vein authentication. This technology is highly secure because it uses information contained within the body and is also highly accurate because the pattern of veins in the palm is complex and unique to each individual.	International standardization of biometric authentication technology is now in progress,

		Moreover, its contactless feature gives it a hygienic advantage over other biometric authentication technologies. This paper also describes some examples of financial solutions and product applications for the general market that have been developed based on this technology.	centred on ISO/ITC JTC1/SC37. Items targeted for standardization include application interfaces, personal data formats, methods for evaluating authentication accuracy, and guidelines for applying this technology to various solutions. Japan has its own national committee for this technology and has established the Biometrics Security Consortium (BSC). Both of these organizations aim to standardize the implementation of biometric authentication technology in Japan.
12. Biometric – Fingerprint	IDEMIA. (2021). Contactless fingerprint. Retrieved 2022, from https://www.idemia.com/contactless-fingerprint	Two versions of the MorphoWave™ contactless fingerprint scanner are available: MorphoWave™ XP: an extended Performance biometric reader for the most demanding projects; up to 100K user records in 1:n mode, up to 60 people per minute, with a large color tactile screen for user interaction, and time and attendances use cases MorphoWave™ SP: all of the essentials of MorphoWave technology with a Simplified Profile up to 10K user records, and a simplified user interface via multicolor LED indicators	
13. Biometric – Fingerprint	Barni, M., Bianchi, T., Catalano, D., Raimondo, M. D., Labati, R. D., Failla, P., . . . Scotti, F. (2010). A privacy-compliant fingerprint recognition system based on	In this paper we propose a novel complete demonstrator based on a distributed biométrie system that is capable to protect the privacy of the	The demonstrator has been fully implemented and tested in real applicative conditions. Experimental

	homomorphic encryption and Fingercode templates. Washington, DC, USA: IEEE.	individuals by exploiting cryptosystems. The implemented system computes the matching task in the encrypted domain by exploiting homomorphic encryption and using Fingercode templates. The paper describes the design methodology of the demonstrator and the obtained results. T	results show that this method is feasible in the cases where the privacy of the data is more important than the accuracy of the system and the obtained computational time is satisfactory.
14. Biometric – Voice Recognition	Misra, C., & Hota, M. K. (2018). Hybrid Technique for Voice Recognition, Encryption and Analysis Using MATLAB. Chennai, India: IEEE.	This paper denotes and computes a simple algorithm to recognize voice using pitch making technique and also provides a hybrid technique to encrypt voice using scanned patterns recognition with the help of an alphanumeric password.	the original voice is encrypted using that password to get the encrypted voice.
15. Biometric – Voice Recognition	Patil, K. V. (2018). VOICE ALERT SYSTEM FOR EASY NAVIGATION OF BLINDS USING ZIGBEE AND GPS. Maharashtra, India. Retrieved 2022, from http://ijiit.logicinside.net/archive/volume%206/issue%201/V6I1P01.pdf	A desirable strategy to deal with such issues is to shift more people from personal vehicles to public transport by providing better service (comfort, convenience and so on). The scope of this proposed system is to use speech recognition system for user selected destination entry, and voice module for making announcements about the arrival details. The performance of the proposed system is found to be promising and expected to be valuable in the development of advanced public transportation systems (APTS) in India.	The main advantage of this device is to provide bus alerting system for easy navigation i.e., the user gets the voices which pronounce the bus details along with destination alerts.
16. Biometric - Facial Recognition	Ciftci, O., Choi, E. K. C., & Berezina, K. (2021). Let's face it: are customers ready for facial recognition technology at quick-service restaurants? International Journal of Hospitality Management, 95, 102941.	The biometric identification technology is tested in QSR (Quick Service Restaurants). Provides a study on people's willingness for adoption of this technology from two perspective: A) Loyalty Program Accounts B) Payment Account Authorization by extending UTAUT with additional factors such as customers personal innovation, privacy concern, perceived security, and	FRS is more secure type of authorization. Security can be violated by system's error or an attacker. Trust in FRS is the belief that all components have integrity and are reliable. Security measures should be complaint with biometric data privacy protection laws. Thus, reliable biometric system should be designed to enhance

		trust in the system. Integration of FRS with POS. Organised combination of hardware, software, databases, network that retrieves, transforms, stores, and distributes information	the security and privacy of user that increase the trust in system.
17. Biometric - Facial Recognition	Zhang, W. K., & Kang, M. J. (2019). Factors affecting the use of facial-recognition payment: an example of Chinese consumers. Lee Access, 7, 154360-154374.	FRS technology detects and describes the feature vectors contactless. Major advantage of accessibility and flexibility. Are more secure. The level of security has direct effect on consumers intent to use. Consumers are worried about personal privacy.	FRS has advantage of user friendliness or non-intrusiveness. 3D recognition technology provides relatively reliable identification and can handle wide variety of facial expressions. Soft biometric can be combined with FRS to improve accuracy.
18. Biometric - Facial Recognition	Han, S., Hu, J., Li, W., Zhao, S., Chen, M., Xu, P., & Luo, Y. (2021). From structure to concepts: The two stages of facial expression recognition. Neuropsychologia, 150, 107700.	Study examined the processes of facial structure and emotional concepts in facial expression recognition. Repetition-priming paradigm in combination with event-related potentials (ERP) to examine neurocognitive processing stages of facial expression perception. Results revealed neural mechanisms underlying processes from physical structure to emotional concepts.	The emotional concepts were recognized faster than emotional faces. Study suggests that facial expression recognition consists of two stages from geometrical structure of faces to emotional concepts of facial expression.
19. Biometric - Facial Recognition	Patel, K., Han, H., & Jain, A. K. (2016). Secure face unlock: Spoof detection on smartphones. IEEE transactions on information forensics and security, 11(10), 2268-2283.	Security against the face spoofing attacks requires increased attention. An efficient face spoof detection system is developed. Experimental results on public domain databases. Spoofing attacks can be easily launched. More robust spoof detection models can be built which make use of temporal and contextual information included in multiple video frames.	Approach is effective in cross-database and intra-database testing scenarios.
20. Biometric - General	Rathgeb, C., & Uhl, A. (2011). A survey on biometric cryptosystems and cancelable biometrics. EURASIP journal on information security, 2011(1), 1-25.	Talks about biometric encryption using key binding. The algorithm is summarized in a patent. Algorithm also applicable to other biometrics. Has few issues and challenges. TRANSFORMATION AND	Cancellable biometric transforms are designed in a way that it should be computationally hard to recover the original biometric data. The technique

		ALLIGNMENT OF TRANSFORMED TEMPELATES HAVE TO BE OPTIMIZED.	enhances the privacy and security of biometric systems providing reliable authentication. Issue of alignment significantly effects recognition performance. Standardization on biometric template protection is currently under work in ISO/IEC FCD 24745.
21. Biometric - Facial Recognition	Elloumi, W., Cauchois, C., & Pasqual, C. (2021). Will face recognition revolutionise the shopping experience?. Biometric Technology Today, 2021(3), 8-11.	The article focuses on use of FRS in retail stores. A review of technological options and challenges are provided.	Better depth accuracy is achieved by use of 3d cameras.3D cameras require more space and are costlier than 2D counterparts and use manufacture specific protocol. The way the company plans to enrol users has a strong impact on hardware choices. A customer can do it at home via smartphone, can also enrol at POS using dedicated hardware which offers more possibilities like 3D template. Identification requires centralized database to store templates; it presents high level risk and is complicated to setup with respect to privacy regulations. The main question should no longer be “Do we want to use facial recognition?”, but “How do we want to use this technology.
22. Biometric - Facial Recognition	Bisogni, C., Cascone, L., Dugelay, J. L., & Pero, C. (2021). Adversarial attacks through architectures and spectra in face recognition. Pattern Recognition Letters, 147, 55-62.	The use of Deep Neural Network (DNN) techniques offers fast prediction with high accuracy. However, they can be attacked and fooled. The study provides the way to fool the technique by moving from one spectrum to another. The analysis can be used to implement counterattack measures.	The application field is face recognition. The attacks performed are based on fast gradient sign method. Cross spectral attack can be used to fool major DNN techniques.

23. Biometric - Facial Recognition	FRVT Face Mask Effects https://pages.nist.gov/frvt/html/frvt_facemask.html	FVRT test result with Covid-19 face mask	Different vendors facial recognition accuracy with face mask
24. Biometric - Facial Recognition	Questions about Facial Recognition 2021 https://www.csis.org/analysis/questions-about-facial-recognition	improvements in facial recognition technology, especially in how algorithms are developed and trained, will continue to reduce the risks of error and bias. Like all new technologies, continued improvement reduces risk, and concerns based on how facial recognition technology worked even a few years ago are now out of date. To help improve public understanding of facial recognition, we have reviewed the following questions to address some of the leading concerns.	In ideal conditions, facial recognition systems have extremely high accuracy. As of December 2020, the best face identification algorithm has an error rate of just 0.1 percent. This degree of accuracy requires consistency in the images' lighting and positioning and ensuring that the facial features of the subjects are clearly visible and not obscured. In real-world deployments, accuracy rates can be much lower. NIST's 2017 Face in Video Evaluation (FIVE) tested algorithms' performance when applied to video captured in settings like airport boarding gates and sports venues. The test found that when using footage of individuals walking through a sporting venue—a challenging environment where it is difficult to capture clear images of the subjects—the algorithms being tested had accuracies ranging between 36 percent and 87 percent, depending on camera placement.
25. Biometric - Facial Recognition	Omoyiola, B. O. (2018). Overview of biometric and facial recognition techniques. IOSR journal of computer engineering (IOSRJCE), 20(4), 1-5.	The field of biometrics is a branch of IT that is growing rapidly. The technologies are automated mechanisms of identifying an individual based on their biological and behavioural characteristics. This chapter focuses on the biometric systems, facial	Security has become a major issue globally and in order to manage the security challenges and reduce the security risks in the world, biometric systems such as face detection and

		detection and facial recognition, and evaluation of different face recognition methods.	recognition systems have been built. These systems are capable of providing biometric security, crime prevention and video surveillance services because of their inbuilt verification and identification capabilities. This has become possible due to technological advancement in the fields of automated face analysis, machine learning and pattern recognition. In the paper, we review some biometric and facial recognition techniques.
26. Biometric - Facial Recognition	Face biometrics deployed for train station security in Asia, Germans pushback on public surveillance 2020 https://www.biometricupdate.com/202001/face-biometrics-deployed-for-train-station-security-in-asia-germans-pushback-on-public-surveillance	Beijing station adopted facial recognition for ticketing	Beijing Railway Station has deployed facial recognition in 30 self-service ticket checking machines to reduce processing times during the 40-day Spring Festival, according to Beijing International. The institution expects more than 8.34 million passengers will use the service.
27. Biometric - Facial Recognition	IDEMIA VISIONPASS™ FACIAL RECOGNITION 2021 https://www.aranasecurity.com/products/idemia-visionpass-face-recognition/	Facial recognition product from the best vendor - IDEMIA in 2021(it is proved by CSIS organization). The product has the following features: true security. VisionPass incorporates IDEMIA's latest spoof detection mechanisms and is capable of coping with face changes (change of haircut, glasses, helmet, etc.).2. easy deployment. VisionPass can be deployed at any location: indoor or outdoor. In addition to biometrics, it natively supports Prox, iClass, MIFARE, DESFire cards and PIN codes. 3. unique performance. Thanks to the association of a state-of-the-art optical set combining 2D/3D/IR	Technical solution of facial recognition -In this product, IDEMIA associated its latest advances in Artificial Intelligence and facial recognition algorithms with a state-of-the-art optical set combining 2D, 3D and infra-red cameras. Can be deployed at any location: indoor or outdoor. VisionPass provides both a high level of security and real user convenience.

		cameras with IDEMIA's latest advances in AI and image processing, VisionPass provides both a high level of security and real user convenience.	
28. Biometric - Facial Recognition	Ghiass, R. S., Arandjelović, O., Bendada, H., & Maldague, X. (2013, August). Infrared face recognition: a literature review. In The 2013 International Joint Conference on Neural Networks (IJCNN) (pp. 1-10). IEEE.	Automatic face recognition (AFR) is an area with immense practical potential which includes a wide range of commercial and law enforcement applications, and it continues to be one of the most active research areas of computer vision. Even after over three decades of intense research, the state-of-the-art in AFR continues to improve, benefiting from advances in a range of different fields including image processing, pattern recognition, computer graphics and physiology. However, systems based on visible spectrum images continue to face challenges in the presence of illumination, pose and expression changes, as well as facial disguises, all of which can significantly decrease their accuracy. Amongst various approaches which have been proposed in an attempt to overcome these limitations, the use of infrared (IR) imaging has emerged as a particularly promising research direction. This paper presents a comprehensive and timely review of the literature on this subject.	Technical solution of facial recognition - The use of IR imaging for AFR, as an alternative to visual spectrum-based approaches, has attracted substantial research and commercial attention as a modality which could facilitate greater robustness to illumination and facial expression changes, facial disguises and dark environments.
29. Biometric - Facial Recognition	New ABC eGates: smaller footprint, modular design and faster passenger processing 2021 https://www.thalesgroup.com/en/markets/digital-identity-and-security/government/eborder/egates	The new Thales Gemalto ABC eGates combine expertise in document verification, passenger biometric authentication with an optimized and modular hardware solution to automate border control. They provide greater flexibility with regards to the	Automation of the border control process with state-of-the-art passenger authentication software leveraging biometric data contained in the ePassport and captured live at the gate, Reduced waiting times and passengers carrying out the checks themselves in just a few seconds, allowing for greater

		airport floor and passenger flow management and process passengers faster.	empowerment and more dwell time in a duty-free area, Flexibility in terms of hardware design and process management for the benefit of both airports and border authorities.
30. Biometric - Facial Recognition	Facial Recognition, Authentication and Mobile Security Token 2021 http://www.solidpass.com/authentication-methods/facial-recognition-authentication.html	SolidPass supports facial recognition as an added layer of authentication and security. Facial recognition is a form of biometric authentication. SolidPass harnesses the advanced camera capabilities of the latest smartphones to perform facial recognition.	uses the standards-based strong two-factor authentication HOTP algorithm endorsed by OATH, Easy integration of SolidPass into existing IT back-ends，RADIUS Server Support，LDAP support，SOAP/Webservices，Microsoft IAG 2007 SSL VPN，BlackBerry Enterprise Server (BES) support，Citrix Secure Access Gateway Cisco VPN， SOA architecture
31. Biometric - Facial Recognition	How Accurate are Facial Recognition Systems – and Why Does It Matter? (2020). https://www.csis.org/blogs/technology-policy-blog/how-accurate-are-facial-recognition-systems-%E2%80%93-and-why-does-it-matter	Accuracy performance of facial recognition	Facial recognition has improved dramatically in only a few years. As of April 2020, the best face identification algorithm has an error rate of just 0.08% compared to 4.1% for the leading algorithm in 2014, according to tests by the National Institute of Standards and Technology (NIST).
32. Biometric - Facial Recognition	Ciftci, O., Choi, E. K. C., & Berezina, K. (2021). Let's face it: are customers ready for facial recognition technology at quick-service restaurants?. International Journal of Hospitality Management, 95, 102941.	This study aims to provide an integrated model that examines the determinants of customer intention to use facial recognition systems (FRS) in quick-service restaurants (QSRs). An extended model built based on the unified theory of acceptance and use of technology (UTAUT) was tested via structural equation modeling (SEM) using data collected from a sample of 558 QSR customers.	The results showed that perceived performance expectancy, social influence, and trust in the system significantly and positively affect customer intention to use FRS to access loyalty and payment accounts. Furthermore, customer hedonic motivation had a positive effect on the intention to use FRS for authorization to

			their loyalty accounts, but no effect on the intention to use this technology for payment account authorization. The developed model would be helpful to managers for making a decision of utilizing FRS in QSRs and promoting the technology among customers.
33. Biometric - Facial Recognition	Zhang, L., Li, X., Nie, L., Yang, Y., & Xia, Y. (2015). Weakly supervised human fixations prediction. IEEE transactions on cybernetics, 46(1), 258-269.	This paper proposes weakly supervised fixations prediction, which leverages image labels to improve accuracy of human fixations prediction. The proposed model hierarchically discovers objects as well as their spatial configurations.	Starting from the raw image pixels, we sample superpixels in an image, thereby seamless object descriptors termed object-level graphlets (oGLs) are generated by random walking on the superpixel mosaic. Then, a manifold embedding algorithm is proposed to encode image labels into oGLs, and the response map of each prespecified object is computed accordingly.
34. Biometric - Facial Recognition	Akhtar, Z., & Rattani, A. (2017). A face in any form: new challenges and opportunities for face recognition technology. Computer, 50(4), 80-90	Despite new technologies that make face detection and recognition more sophisticated, long-recognized problems in security, privacy, and accuracy persist. Refining this technology and introducing it into new domains will require solving these problems through focused interdisciplinary efforts among developers, researchers, and policymakers	Reveals significant progress over the past two decades as well as unresolved issues related to accuracy, security, and user privacy. We are confident that, with time and focused interdisciplinary research and development, face recognition will reach its full potential in a wide range of application domains.
35. Biometric - Facial Recognition	Shu, Z., Yumer, E., Hadap, S., Sunkavalli, K., Shechtman, E., & Samaras, D. (2017). Neural face editing with intrinsic image disentangling. In Proceedings of the IEEE conference on computer vision and pattern recognition (pp. 5541-5550).	Traditional face editing methods often require a number of sophisticated and task specific algorithms to be applied one after the other --- a process that is tedious, fragile, and computationally intensive. In this paper, we propose an end-to-end generative adversarial network that infers a face-specific	We show that this network can be trained on "in-the-wild" images by incorporating an in-network physically-based image formation module and appropriate loss functions. Our disentangling latent representation allows for semantically

		disentangled representation of intrinsic face properties, including shape (i.e. normals), albedo, and lighting, and an alpha matte.	relevant edits, where one aspect of facial appearance can be manipulated while keeping orthogonal properties fixed, and we demonstrate its use for a number of facial ed
36. Biometric - Facial Recognition	Hao, Z., Liu, Y., Qin, H., Yan, J., Li, X., & Hu, X. (2017). Scale-aware face detection. In Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (pp. 6186-6195).	Convolutional neural network (CNN) based face detectors are inefficient in handling faces of diverse scales. They rely on either fitting a large single model to faces across a large scale range or multi-scale testing. Both are computationally expensive. We propose Scale-aware Face Detector (SAFD) to handle scale explicitly using CNN, and achieve better performance with less computation cost. Prior to detection, an efficient CNN predicts the scale distribution histogram of the faces. Then the scale histogram guides the zoom-in and zoom-out of the image.	Since the faces will be approximately in uniform scale after zoom, they can be detected accurately even with much smaller CNN. Actually, more than 99% of the faces in AFW can be covered with less than two zooms per image. Extensive experiments on FDDB, MALF and AFW show advantages of SAFD
37. Biometric - Facial Recognition	Hu, P., & Ramanan, D. (2017). Finding tiny faces. In Proceedings of the IEEE conference on computer vision and pattern recognition (pp. 951-959).	Though tremendous strides have been made in object recognition, one of the remaining open challenges is detecting small objects. We explore three aspects of the problem in the context of finding small faces: the role of scale invariance, image resolution, and contextual reasoning. While most recognition approaches aim to be scale-invariant, the cues for recognizing a 3px tall face are fundamentally different than those for recognizing a 300px tall face. We take a different approach and train separate detectors for different scales. To maintain efficiency, detectors are trained in a multi-task fashion: they make use of features extracted from multiple layers of single (deep) feature	We show that context is crucial, and define templates that make use of massively-large receptive fields (where 99% of the template extends beyond the object of interest). Finally, we explore the role of scale in pre-trained deep networks, providing ways to extrapolate networks tuned for limited scales to rather extreme ranges. We demonstrate state-of-the-art results on massively-benchmarked face datasets (FDDB and WIDER FACE). In particular, when compared to prior art on WIDER FACE, our results reduce error by a factor of 2

		hierarchy. While training detectors for large objects is straightforward, the crucial challenge remains training detectors for small objects.	(our models produce an AP of 82% while prior art ranges from 29-64%).
38. Biometric - Facial Recognition	Zhang, L., Li, X., Nie, L., Yang, Y., & Xia, Y. (2015). Weakly supervised human fixations prediction. IEEE transactions on cybernetics, 46(1), 258-269.	This paper proposes weakly supervised fixations prediction, which leverages image labels to improve accuracy of human fixations prediction. The proposed model hierarchically discovers objects as well as their spatial configurations.	Starting from the raw image pixels, we sample superpixels in an image, thereby seamless object descriptors termed object-level graphlets (oGLs) are generated by random walking on the superpixel mosaic. Then, a manifold embedding algorithm is proposed to encode image labels into oGLs, and the response map of each prespecified object is computed accordingly.
39. Biometric - Facial Recognition	Zhang, L., Gao, Y., Zimmermann, R., Tian, Q., & Li, X. (2014). Fusion of multichannel local and global structural cues for photo aesthetics evaluation. IEEE Transactions on Image Processing, 23(3), 1419-1429.	Propose a new photo aesthetics evaluation framework, focusing on learning the image descriptors that characterize local and global structural aesthetics from multiple visual channels. In particular, to describe the spatial structure of the image local regions, we construct graphlets small-sized connected graphs by connecting spatially adjacent atomic regions.	Experimental results show that: 1) the visualized graphlets explicitly capture the aesthetically arranged atomic regions; 2) the proposed approach generalizes and improves four prominent aesthetic rules; and 3) our approach significantly outperforms state-of-the-art algorithms in photo aesthetics prediction.
40. Biometric - Facial Recognition	Zhang, W. K., & Kang, M. J. (2019). Factors affecting the use of facial-recognition payment: an example of Chinese consumers. IEEE Access, 7, 154360-154374.	The purpose of this study is to explore the factors influencing consumers' willingness to use facial-recognition payment systems. This study has selected security, visibility, and expected effort and social image as the feature variables of the facial-recognition payment system.	Results in this paper shows that the safety, security, visibility and social image will affect consumers' intent to use the system. It can also influence consumers' intent to use through perceived usefulness.
41. Biometric - Facial Recognition	Abate, A. F., Nappi, M., Riccio, D., & Sabatino, G. (2007). 2D and 3D face recognition: A survey. Pattern recognition letters, 28(14), 1885-1906.	This paper provides an “ex cursus” of recent face recognition research trends in 2D imagery and 3D model based algorithms. To simplify comparisons across different approaches, tables containing	Biometrics represents a valid alternative but they suffer of drawbacks as well. Iris scanning, for example, is very reliable but too intrusive; fingerprints are socially

		different collection of parameters (such as input size, recognition rate, number of addressed problems) are provided.	accepted, but not applicable to non-consentient people. On the other hand, face recognition represents a good compromise between what's socially acceptable and what's reliable, even when operating under controlled conditions.
42. Biometric - Facial Recognition	Crumpler, James A. Lewis and William (2021). Questions about Facial Recognition. https://csis-website-prod.s3.amazonaws.com/s3fs-public/publication/210203_Lewis_Facial_Recognition_1.pdf	We reviewed the most salient of these concerns for accuracy and for their implications for policymaking, and came to several conclusions. Our first conclusion is that to reduce concerns about facial recognition, Congress needs to pass effective privacy legislation to govern digital technologies.	Improvements in facial recognition technology, especially in how algorithms are developed and trained, will continue to reduce the risks of error and bias. Like all new technologies, continued improvement reduces risk, and concerns based on how facial recognition technology worked even a few years ago are now out of date.
43. Biometric - Facial Recognition	Elloumi, W., Cauchois, C., & Pasqual, C. (2021). Will face recognition revolutionise the shopping experience?. Biometric Technology Today, 2021(3), 8-11.	Today, facial recognition is a prevalent though controversial technology. It has become established as the most natural means of biometric identification, as it doesn't require any contact or physical interaction by the end user – a feature that has become even more important during the coronavirus pandemic.	Facial recognition is one of the most adopted biometric modalities that's now being used for many and varied use-cases, such as in payments or loyalty experiences.
44. Biometric - Facial Recognition	Omoyiola, B. O. (2018). Overview of biometric and facial recognition techniques. IOSR journal of computer engineering (IOSRJCE), 20(4), 1-5.	In the paper, we review some biometric and facial recognition techniques.	Security has become a major issue globally and in order to manage the security challenges and reduce the security risks in the world, biometric systems such as face detection and recognition systems have been built. These systems are capable of providing biometric security, crime prevention and

			video surveillance services because of their inbuilt verification and identification capabilities. This has become possible due to technological advancement in the fields of automated face analysis, machine learning and pattern recognition.
45. Biometric - Facial Recognition	Moriuchi, Emi. (2021). An empirical study of consumers' intention to use biometric facial recognition as a payment method. Psychology & Marketing. 38. 10.1002/mar.21495.	The study investigated antecedents that affect consumers' trust of, attitude toward, and usage of a biometric payment system. Based on the results from Study 1, Study 2 was conducted by introducing two shopping modalities in the study.	The results show that consumers would rather use a biometric payment system in stores than online. Between the two modalities, consumers' trust and attitude toward the technology have a stronger mediating role for online than in-store toward their intention to use. In addition, self-efficacy consistently moderates the antecedents (performance expectation and perceived risk) and their intention to use.
46. Biometric - Facial Recognition	Grother, P. J., Ngan, M. L., & Hanaoka, K. K. (2018). Ongoing face recognition vendor test (frvt) part 2: Identification.	This report updates and extends NIST Interagency Report 8238, documenting performance of new face recognition algorithms submitted for evaluation to NIST in November 2018. The algorithms implement one-to-many identification of faces appearing in two- dimensional images. Three datasets were used - the primary dataset is comprised of 26.6 mil- lion reasonably well-controlled live portrait photos of 12.3 million individuals. Three smaller datasets containing more unconstrained photos are also used: 200 thousand side-view images; 3.2 million	The report will be useful for comparison of face recognition algorithms and assessment of absolute capability. There is an additional appendix to this NISTIR, which contains individual reporting for each algorithm submitted to FRVT 1:N.

		webcam images; 2.5 million photojournalism and amateur photographer photos.	
47. Biometric - Voice Recognition	The Complete Guide to Speech Recognition Technology 2020 https://summalinguae.com/language-technology/guide-to-speech-recognition-technology/-:~:text=In%202017%2C%20Google%20boasted%20a,fall%20below%20the%205%25%20threshold.	This report takes a brief look at the history of speech recognition technology, start with how it works and some devices that make use of it. Then we'll examine what might be just around the corner.	Key findings: Mobile app voice integration, Individualized experiences, Smart displays
48. Biometric - Voice Recognition	Patil, K. V. (2018). Voice alert system for easy navigation of blinds using zigbee and GPS.	How voice alert system helps disability people to take the bus. This device use speech recognition system for user selected destination entry, and voice module for making announcements about the arrival details. The performance of the proposed system is found to be promising and expected to be valuable in the development of advanced public transportation systems (APTS) in India.	Navigate blind people's locations and plan their trip by their voice automatically use speech recognition system for user selected destination entry, the performance of the proposed system is promising
49. Biometric - Voice Recognition	Misra, C., & Hota, M. K. (2018, April). Hybrid technique for voice recognition, encryption and analysis using MATLAB. In 2018 International Conference on Communication and Signal Processing (ICCSP) (pp. 0200-0203). IEEE.	With the development of wireless and communication, there has also been development in voice recognition and voice encryption techniques to provide security to users. This paper denotes and computes a simple algorithm to recognize voice using pitch making technique and also provides a hybrid technique to encrypt voice using scanned patterns recognition with the help of an alphanumeric password.	How the voice is encrypted in order to get the encrypted voice. Simple algorithm to use pitch making techniques. Hybrid technique to encrypt voice using scanned patterns. Original voice is encrypted using that password to get the encrypted voice
50. Biometric - Fingerprint Recognition	How Accurate are today's Fingerprint Scanners? Limitations, Errors and Their Effect on the Accuracy 2021 https://www.bayometric.com	It demonstrates how accurate today's fingerprint scanners are, its limitations, errors and their effect on the accuracy. Today, fingerprint scanners enjoy widespread popularity and growing rate of deployment sin all sorts of applications. One of the	This delicate balance of convenience and security is highly dependent on fingerprint matching accuracy. Several studies have shown that modern fingerprint recognition systems are highly

		reasons of the growing penetration of fingerprint recognition devices is that they have been able to maintain the delicate balance between the convenience and the security. However, there are still several issues, errors and limitations that this technology has to deal with. There are still challenges and limitations in terms of technology, population coverage and security, however, most these challenges can be and will be addressed at some point in future.	accurate. The best system was accurate 98.6 percent of the time on single-finger tests, 99.6 percent of the time on two-finger tests, and 99.9 percent of the time for tests involving four or more fingers. These accuracies were obtained for a false positive rate of 0.01 percent
51. Biometric - Fingerprint Recognition	Barni, M., Bianchi, T., Catalano, D., Di Raimondo, M., Labati, R. D., Failla, P., ... & Scotti, F. (2010, September). A privacy-compliant fingerprint recognition system based on homomorphic encryption and fingercode templates. In 2010 Fourth IEEE International Conference on Biometrics: Theory, Applications and Systems (BTAS) (pp. 1-7). IEEE.	The privacy protection of the biometric data is an important research topic, especially in the case of distributed biometric systems. In this scenario, it is very important to guarantee that biometric data cannot be steeled by anyone, and that the biometric clients are unable to gather any information different from the single user verification/identification. In a biométrie system with high level of privacy compliance, also the server that processes the biométrie matching should not learn anything on the database and it should be impossible for the server to exploit the resulting matching values in order to extract any knowledge about the user presence or behaviour. Within this conceptual framework, in this paper we propose a novel complete demonstrator based on a distributed biométrie system that is capable to protect the privacy of the individuals by exploiting cryptosystems. The implemented system computes the matching task in the encrypted domain by exploiting homomorphic encryption and using	Distributed biometric system that is capable to protect the privacy of the individuals by exploiting cryptosystems. Biométrie matching should not learn anything on the database. Propose complete demonstrator based on a distributed biométrie system that is capable to protect the privacy of the individuals by exploiting cryptosystems. Computes the matching task in the encrypted domain by exploiting homomorphic encryption and using Fingercode templates. Experimental results show that this method is feasible in the cases where the privacy of the data is more important than the accuracy of the system and the obtained computational time is satisfactory.

		Fingercode templates. The paper describes the design methodology of the demonstrator and the obtained results. The demonstrator has been fully implemented and tested in real applicative conditions. Experimental results show that this method is feasible in the cases where the privacy of the data is more important than the accuracy of the system and the obtained computational time is satisfactory.	
52. Biometric - Fingerprint Recognition	Contactless fingerprint (2021). https://www.idemia.com/contactless-fingerprint	contactless fingerprint technical solution	IDEMIA's MorphoWave™ contactless fingerprint solution scans and verifies 4 fingerprints in less than 1 second, through a fully touchless hand wave gesture. Thanks to the simplicity of this gesture, the throughput can reach up to 50 people per minute.
53. Biometric - Iris Recognition	Rajasekar, Vani & J, Premalatha & Sathya, K.. (2020). Enhanced Biometric Recognition for Secure Authentication using Iris Preprocessing and Hyper Elliptic Curve Cryptography. 10.21203/rs.2.23196/v1.	The proposed study uses 2D Gabor filter approach for perfect feature extraction in iris preprocessing. Light weight cryptographic scheme called HECC was employed to encrypt the iris template to avoid intentional attack by the intruders. The benchmark CASIA Iris V-4 and IITD Iris datasets were used in the proposed approach for experimental analysis.	The result analysis witnessed that the prime objective of the research such as lesser false acceptance rate, lesser false rejection rate, maximum accuracy of 99.74%, maximum true acceptance rate of 100%, and minimal recognition time of 3 seconds has been achieved. Also, it has been identified that the proposed study outperforms other existing well-known techniques.
54. Biometric - Palm Recognition	Palm Vein Pattern Authentication Technology (2021). https://www.fujitsu.com/	Contactless palm vein authentication technology is being incorporated into various financial solution products for use in public places. This paper introduces palm vein authentication technology and some examples of its application to financial	Fujitsu has developed a contactless palm vein pattern authentication technology that uses vascular patterns as personal identification data. Vein recognition technology is secure because the

		solutions. It then describes PalmSecure, an authentication product that Fujitsu has developed for the general market, and the company's key milestones in an effort to standardize PalmSecure for biometric authentication	authentication data exists inside the body and is therefore very difficult to forge. It is also highly accurate — in testing using 140,000 palm profiles of 70,000 individuals, it had a false acceptance rate of less than 0.00008% and a false rejection rate of 0.01%.
55. Biometric -Social acceptance	Jain, A. K., & Kumar, A. (2012). Biometric recognition: an overview. Second generation biometrics: The ethical, legal and social context, 49-79.	Presents an overview of biometrics, some of the emerging biometric technologies and their limitations, and examines future challenges	The design and suitability of biometric technology for person identification depends on the application requirements. These requirements are typically specified in terms of identification accuracy, throughput, user acceptance, system security, robustness, and return on investment. The next generation biometric technology must overcome many hurdles and challenges to improve the recognition accuracy. These include ability to handle poor quality and incomplete data, achieve scalability to accommodate hundreds of millions of users, ensure interoperability, and protect user privacy while reducing system cost and enhancing system integrity.
56. Biometric -End user acceptance	Miltgen, C. L., Popovič, A., & Oliveira, T. (2013). Determinants of end-user acceptance of biometrics: Integrating the "Big 3" of technology acceptance with privacy context. Decision support systems, 56, 103-114.	Propose an integrated approach of end-user acceptance of biometric system. The model is based on TAM, DOI and UTAUT along with trust-privacy literature. Technology adoption theory is extended by adding the potential recommendation power.	We first confirm the influence of renowned technology acceptance variables such as compatibility, perceived usefulness, facilitating conditions on biometrics systems acceptance and further recommendation. Second, prior

			factors such as concern for privacy, trust in the technology, and innovativeness also prove to have an influence. Third, unless innovativeness, the most important drivers to explain biometrics acceptance and recommendation are not from the traditional adoption models (TAM, DOI, and UTAUT) but from the trust and privacy literature (trust in technology and perceived risk).
57. Biometric – General	Shaikh, S. A., & Rabaiotti, J. R. (2010). Characteristic trade-offs in designing large-scale biometric-based identity management systems. Journal of Network and Computer Applications, 33(3), 342-351.	Biometric-based identity management systems are deemed to be the new solution to address the challenges of global security and citizenship. While such systems do prove effective, the nature of biometric technology, the costs involved, and increasing threats to theft and loss of data bring with it a variety of other considerations that cannot be ignored. We approach such systems from the perspective of large-scale high-volume public deployments.	We find that various characteristics of such deployments present a trade-off, where emphasis on one undermines the other. Such characteristic trade-off spaces are described and explored in this paper. The ultimate contribution lies in the understanding of such trade-off spaces for the purposes of optimal design of such systems. We use our approach to analyse the recently launched Identity Card scheme in the United Kingdom.
58. Biometric – General review	Biometrics: Driven by Standardized Authentication, Adopted by Consumers 2020 https://www.paymentsjournal.com/by-2024-how-many-smartphone-owners-will-use-biometrics/	Mercator market research indicates biometric use is increasing even as consumers adopt a greater variety of methods choosing among fingerprint, facial recognition, and voice recognition. Biometrics are important because they utilize new mobile security hardware and software to revamp authentication, lower the risk of fraud, address the mandates of the European Union's revised Payment	The statistics of range of facial recognition to phones. By 2024, Mercator forecasts that 66% of smartphone owners will use biometrics for authentication. Currently, Mercator estimates that 41% of smartphone owners are using biometrics. Just one year ago, in 2019 only 27% of consumers used biometrics to authenticate. Although fingerprint

		Services Directive (PSD2), and induce changes in consumer behaviour.	readers remain the top option for authentication, an increasing percentage of users are reporting facial and voice recognition. Voice recognition increased to 20% of biometric authentication in the last year – up from 11% in 2019. Facial recognition jumped to nearly 30% of biometric authentication, up from 11% in 2019. Phone brands play a big role in dictating authentication methods, with Android and iPhone owners clearly emerging as more likely to use voice and facial recognition.
59. Biometric – General review	Hollnagel, J., & Fook, A. (2019). The Future of Fare Media in Automated Fare Collection Systems for Urban Mobility in the Latin America and Caribbean Region.	Presents Automated Fare Collection Practices. Challenges and opportunities of new fare media. Technologies and changemakers.	Presents various Mobile and Biometric enabled Payment Technologies used in transportation. Discusses the factors to consider when deciding on a new fare media.
60. Biometric – General review	Gudavalli, M., Raju, S. V., Babu, A. V., & Kumar, D. S. (2012, March). Multimodal Biometrics--Sources, Architecture and Fusion Techniques: An Overview. In 2012 International Symposium on Biometrics and Security Technologies (pp. 27-34). IEEE.	Studies have demonstrated that multimodal biometric systems can achieve better performance compared with Unimodal systems. We discuss here different multimodal sources, multimodal architectures & different fusion techniques used in multimodal biometric systems.	One of the methods to overcome these problems is to make use of multimodal biometric authentication systems, which combine information from multiple modalities to arrive at a decision. Multimodal biometric systems are those which utilize, or capability of utilizing, more than one physiological or behavioral characteristic for enrolment, verification, or identification.
61. Biometric – General review	Pai, C. K., Wang, T. W., Chen, S. H., & Cai, K. Y. (2018). Empirical study on Chinese tourists' perceived trust	For biometric systems, the security of data can be violated as a result of a system error when it may identify one person as another one or using fake	It showed that the perceived security of FRS in hotels has a positive influence on trust in technology (Pai, 2018).

	and intention to use biometric technology. Asia Pacific Journal of Tourism Research, 23(9), 880-895.	biometric or attacked by a hacker. Perceived security was shown to affect several factors, including consumer trust in technology. There are significant positive direct and indirect effects of perceived security on customer behaviour intentions to use biometric technologies.	
62. Biometric – General review	Rajasekar, V., Predić, B., Saracevic, M., Elhoseny, M., Karabasevic, D., Stanujkic, D., & Jayapaul, P. (2022). Enhanced multimodal biometric recognition approach for smart cities based on an optimized fuzzy genetic algorithm. Scientific Reports, 12(1), 1-11.	This paper proposes an enhanced multimodal biometric technique for a smart city that is based on score-level fusion. Specifically, the proposed approach provides a solution to the existing challenges by providing a multimodal fusion technique with an optimized fuzzy genetic algorithm providing enhanced performance.	Experiments with different biometric environments reveal significant improvements over existing strategies. The result analysis shows that the proposed approach provides better performance in terms of the false acceptance rate, false rejection rate, equal error rate, precision, recall, and accuracy. The proposed scheme provides a higher accuracy rate of 99.88% and a lower equal error rate of 0.18%. The vital part of this approach is the inclusion of a fuzzy strategy with soft computing techniques known as an optimized fuzzy genetic algorithm.
63. Biometric – General review	Millett, L. I., & Pato, J. N. (2010). Biometric recognition: Challenges and opportunities. National Academies Press.	Biometric recognition--the automated recognition of individuals based on their behavioural and biological characteristic--is promoted to help identify terrorists, provide better control of access to physical facilities and financial accounts, and increase the efficiency of access to services and their utilization.	Biometric recognition has been applied to identification of criminals, patient tracking in medical informatics, and the personalization of social services, among other things. In spite of substantial effort, however, there remain unresolved questions about the effectiveness and management of systems for biometric recognition, as well as the

			appropriateness and societal impact of their use.
64. Biometric – General review	Venkatesh, V., Morris, M. G., Davis, G. B., & Davis, F. D. (2003). User acceptance of information technology: Toward a unified view. MIS quarterly, 425-478.	In this paper, we (1) review user acceptance literature and discuss eight prominent models, (2) empirically compare the eight models and their extensions, (3) formulate a unified model that integrates elements across the eight models, and (4) empirically validate the unified model.	The paper makes several recommendations for future research including developing a deeper understanding of the dynamic influences studied here, refining measurement of the core constructs used in UTAUT, and understanding the organizational outcomes associated with new technology use.
65. Biometric – General review	Mordini, E., & Tzovaras, D. (Eds.). (2012). Second generation biometrics: The ethical, legal and social context (Vol. 11). Springer Science & Business Media.	One of the first books on second generation biometrics and the first on ethical, social and privacy implication of them. Includes chapters from neuroscientists, psychologists, psychiatrists, jurists, social scientists, philosophers, ethicists, as well as technologists	ethical, social and privacy implication of biometrics
66. Biometric – General review	Unar, J. A., Seng, W. C., & Abbasi, A. (2014). A review of biometric technology along with trends and prospects. Pattern recognition, 47(8), 2673-2688.	An extensive review of biometric technology is presented here. Besides the mono-modal systems, the article also discusses multi-modal biometric systems along with their architecture and information fusion levels.	The paper along with the exemplary evidences highlights the potential for biometric technology, market value and prospects.
67. Biometric – General review	Unar, J. A., Seng, W. C., & Abbasi, A. (2014). A review of biometric technology along with trends and prospects. Pattern recognition, 47(8), 2673-2688.	The automated FRS computes 2D or 3D features. 3D based recognition is new trend which rectifies problems in 2D. However, they cannot guarantee reliable identification in presence of artifacts. Artifacts have significant impact on accuracy. In	To make FRS robust researchers have proposed recognition based on facial thermograph. Few studies have claimed to provide better accuracy in terms of detection, localization, and segmentation. Challenges include sensitivity to

		addition, the expensive imaging hardware also limits the use.	illumination, ageing, presence of occlusions. Iris recognition is very prominent due to non-invasive image acquisition and clear visibility at a distance. Multi-modal based techniques offer better accuracy and security.
68. Biometric – General review	Zhang, L., Gao, Y., Hong, C., Feng, Y., Zhu, J., & Cai, D. (2013). Feature correlation hypergraph: exploiting high-order potentials for multimodal recognition. IEEE transactions on cybernetics, 44(8), 1408-1419.	In computer vision and multimedia analysis, it is common to use multiple features (or multimodal features) to represent an object. For example, to well characterize a natural scene image, we typically extract a set of visual features to represent its colour, texture, and shape. However, it is challenging to integrate multimodal features optimally. Since they are usually high-order correlated, e.g., the histogram of gradient (HOG), bag of scale invariant feature transform descriptors, and wavelets are closely related because they collaboratively reflect the image texture. Nevertheless, the existing algorithms fail to capture the high-order correlation among multimodal features. To solve this problem, we present a new multimodal feature integration framework. Particularly, we first define a new measure to capture the high-order correlation among the multimodal features, which can be deemed as a direct extension of the previous binary correlation.	Therefore, we construct a feature correlation hypergraph (FCH) to model the high-order relations among multimodal features. Finally, a clustering algorithm is performed on FCH to group the original multimodal features into a set of partitions. Moreover, a multiclass boosting strategy is developed to obtain a strong classifier by combining the weak classifiers learned from each partition. The experimental results on seven popular datasets show the effectiveness of our approach.

SLAM

Simultaneous localization and mapping (SLAM) creates a map of the surroundings, using lidars, cameras or other sensors, and simultaneously determines the position of the device in it. Mainly used in robotics and for autonomous vehicles, this technology is now being developed for wayfinding solutions for blind people. Ticketing capability could be integrated in SLAM empowered devices. The literature indicates that this technology has come a long way, but is not yet mature for this use case, as much of the attention is still on the algorithms.

SLAM: Evaluation criteria

Table 5. Key evaluation requirements- SLAM

Key requirements	
Technology readiness – now vs. emerging	Essential capabilities proven such as: Precision positioning and wayfinding in indoors: This information can be used for calculating the fares Augmented Reality (AR): this technology can be used for assisting passengers' payments and navigations
Certainty/reliability (e.g., interference)	Indoors: High level of certainty and reliability. Medium outdoor accuracy of 5m [1] High indoor accuracy under 10 cm [2] without the interference from communication radios.
Accurate/very low error rates	Very high accuracy in positioning in sub centimetres using fiducial markers. Without fiducial markers or very far from the markers positioning accuracy will drops to 5m [1]
Secure– not easy to forge, clone	Secure with end-to-end encryption. Private position data acquisition using fiducial markers.

Use case requirements	**Tech solution**
Identification	Account Number can be used for identification

Tokenisation /Authentication	Internet authentications and Tokenisation can be used in the digital tickets to protect user privacy.
Positioning & trip definition: Registration in (begin of ticket) Registration out (end of ticket) Repeat for next leg of trip	SLAM uses precision position data and time for taking decisions and issuing tickets. Fiducial markers can be used to improve SLAM positioning accuracy significantly, also fiducial markers can provide more information about the place or vehicle. Fiducial markers provide information about the vehicle to the SLAM and SLAM can detect be-in/be-out automatically. This information will be sent to a backend for calculating fares
Capacity to process multiple entries simultaneously (large quantities / high throughput) – unless separate lane	Large quantity. All queries are sent to cloud for processing and cloud
Can detect entry in vehicle (as opposed to walking by). Determines with high accuracy which mode of transport has been/is being used	SLAM can read the information on the fiducial markers – similar to QR codes – to detect be-in/be-out to gates and most vehicles. However, required beacons and fiducial markers to be installed in the PT areas.
Execute gate open and close 'just in in time' for gated solutions Consider gated and non-gated – in a variety of use cases: bus, train, tram, ferry, taxi, on demand	Required more research for just in time for gated solution. Position accuracy is good for gates, however network latency can be issue.
Works indoor and outdoor (with and without GPS)	Yes
Cover fixed and variable routes, i.e., cannot rely on fixed infrastructure. Work in taxi's, mini buses, mopeds, bike sharing, etc.	It can cover a wide variety of transports. By automatically scanning QR codes and fiducial markers
High feasibility of installation across all use cases	Requires more research
Low maintenance/Asset Management System (also Resistant to vandalism)	Requires routine updates for maps, however 3rd party companies, such as Google, can be used

Risks/concerns?	SLAM is more suitable for indoor spaces and GNSS can be used for outdoor spaces 3rd Party cloud services are required for SLAM algorithms, and it may be a risk for user privacy.

SLAM: Literature overview

Tech Type	Reference	Summary	Key Point of Interest
1. SLAM positioning algorithm based on smart phone	ZUN NIU, X. Z. (2020). A Continuous Positioning Algorithm Based on RTK and VI-SLAM With Smartphones. Beijing China.	Our study mainly aims to confirm the feasibility of continuous positioning based on RTK and VI-SLAM with the Xiaomi MI 8. An application is developed to execute the functions, including logging images, measurements of IMU, and GPS measurements in Receiver INdependent EXchange (RINEX) format with the Xiaomi MI 8. The performances of RTK with and without the assistance of VI-SLAM are assessed respectively in the urban area.	The experimental results demonstrate that the combination of RTK and VI-SLAM based on smartphones can effectively provide continuous positioning results. We believe our application will facilitate research and development in relation to positioning algorithms.
2. SLAM indoor mapping technologies	Chen, Y., Tang, J., Jiang, C., Zhu, L., Lehtomäki, M., Kaartinen, H., . . . Chen, R. (2018). The Accuracy Comparison of Three Simultaneous Localization and Mapping (SLAM)-Based Indoor Mapping Technologies. Sensors, 18(10), 3228.	In this paper we try to characterize them and provide some extensive references for SLAM or mapping system selection for different applications. Two different indoor scenes (a L shaped corridor and an open style library) were selected to review and compare three different mapping systems, namely: (1) a commercial Matterport system equipped with depth cameras; (2) SLAMMER: a high accuracy small footprint LiDAR with a fusion of hector-slam and graph-slam approaches; and (3) NAVIS: a low-cost large footprint LiDAR with Improved Maximum Likelihood Estimation (IMLE)	The mapping RMS errors of SLAMMER, NAVIS and Matterport were 2.0 cm, 3.9 cm and 4.4 cm, respectively, for the interactively selected features, and the corresponding values using MBR features were 1.7 cm, 3.2 cm and 4.7 cm. The corresponding detection rates for the feature points were 100%, 98.9%, 92.3% for the interactive selected features and 100%, 97.3% and 94.7% for the automated processing.

		algorithm developed by the Finnish Geospatial Research Institute (FGI).	
3. SLAM positioning algorithm	Niu, Z., Zhao, X., Sun, J., Tao, L., & Zhu, B. (2020). A continuous positioning algorithm based on RTK and VI-SLAM with smartphones. IEEE Access, 8, 185638-185650.	The navigation technology has developed rapidly and immensely over the past few decades. Among the multiple navigation technologies, the representative and promising techniques are Real-time Kinematic (RTK) technique and Simultaneous Localization and Mapping (SLAM). RTK can provide real-time positioning results with high accuracy, while SLAM can not only locate the user but also construct a map of the new ambient. The first smartphone, the Xiaomi MI 8, equipped with the dual-frequency Global Navigation Satellite System (GNSS), hit the market in May 2018, providing valid carrier-phase measurements for RTK owe to the developer option of ”Force full GNSS measurements.” Nevertheless, RTK underperforms in urban areas as the buildings and trees can block the satellite signals. RTK cannot even provide positioning results when the GNSS outage happens.	SLAM can effectively make up the drawbacks of RTK as it utilizes no more information than the images. SLAM can also be combined with the Inertial Measurement Unit (IMU) called Visual-Inertial SLAM (VI-SLAM,) with the improvement of accuracy and robustness. Therefore, our study mainly aims to confirm the feasibility of continuous positioning based on RTK and VI-SLAM with the Xiaomi MI 8. An application is developed to execute the functions, including logging images, measurements of IMU, and GPS measurements in Receiver INdependent EXchange (RINEX) format with the Xiaomi MI 8. The performances of RTK with and without the assistance of VI-SLAM are assessed respectively in the urban area. The experimental results demonstrate that the combination of RTK and VI-SLAM based on smartphones can effectively provide continuous positioning results. We believe our application will facilitate research and development in relation to positioning algorithms. Readers have access to this application at https://github.com/Nronaldo/CIGRLogger.
4. SLAM indoor mapping	Röger, C., & Timpf, S. (2018). Indoor mapping for human navigation–a low-cost SLAM solution.	This paper introduces a low-cost Simultaneous Localization And Mapping (SLAM) implementation for generating geodata for human-navigable maps. In contrast to prevalent thinking, we	Basically, there is a need only to map the boundaries of spaces and to highlight walkable places and areas of potential decisions. The SLAM system presented here consists of an Arduino-based robot and controlling SLAMTerminal software. A case study conducted at

		maintain that navigation by people who are not mobility-impaired does not need accurate maps down to millimetres or even centimetres.	the University of Augsburg, Germany shows that the proposed SLAM implementation is capable of producing a map suitable for helping pedestrians to navigate.
5. SLAM - D* algorithm for robot positioning	Labbe, M., & Michaud, F. (2014, September). Online global loop closure detection for large-scale multi-session graph-based SLAM. In 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems (pp. 2661-2666). IEEE.	For large-scale and long-term simultaneous localization and mapping (SLAM), a robot has to deal with unknown initial positioning caused by either the kidnapped robot problem or multi-session mapping. This paper addresses these problems by tying the SLAM system with a global loop closure detection approach, which intrinsically handles these situations. However, online processing for global loop closure detection approaches is generally influenced by the size of the environment.	The proposed graph-based SLAM system uses a memory management approach that only consider portions of the map to satisfy online processing requirements. The approach is tested and demonstrated using five indoor mapping sessions of a building using a robot equipped with a laser rangefinder and a Kinect.
6. SLAM multi-session visual mapping in large-scale environments	McDonald, J., Kaess, M., Cadena, C., Neira, J., & Leonard, J. J. (2011). 6-DOF multi-session visual SLAM using anchor nodes.	This paper describes a system for performing multi-session visual mapping in large-scale environments. Multi-session mapping considers the problem of combining the results of multiple Simultaneous Localisation and Mapping (SLAM) missions performed repeatedly over time in the same environment. The goal is to robustly combine multiple maps in a common metrical coordinate system, with consistent estimates of uncertainty.	Our work employs incremental Smoothing and Mapping (iSAM) as the underlying SLAM state estimator and uses an improved appearance-based method for detecting loop closures within single mapping sessions and across multiple sessions. To stitch together pose graph maps from multiple visual mapping sessions, we employ spatial separator variables, called anchor nodes, to link together multiple relative pose graphs. We provide experimental results for multi-session visual mapping in the MIT Stata Center, demonstrating key capabilities that will serve as a foundation for future work in large-scale persistent visual mapping.

7. SLAM - Omnidirectional wearable system	Murillo, A. C., Gutiérrez-Gómez, D., Rituerto, A., Puig, L., & Guerrero, J. J. (2012, June). Wearable omnidirectional vision system for personal localization and guidance. In 2012 IEEE computer society conference on computer vision and pattern recognition workshops (pp. 8-14). IEEE.	Autonomous navigation and recognition of the environment are fundamental abilities for people extensively studied in computer vision and robotics fields. Expansion of low cost wearable sensing provides interesting opportunities for assistance systems that augment people navigation and recognition capabilities. This work presents our wearable omnidirectional vision system and a novel two-phase localization approach running on it. It runs state-of-the-art real time visual odometry adapted to catadioptric images augmented with topological-semantic information.	The presented approach benefits from using wearable sensors to improve visual odometry results with true scaled solution. The wide field of view of catadioptric vision system used makes features last longer in the field of view and allows more compact location representation which facilitates topological place recognition. Experiments in this paper show promising ego-localization results in realistic settings, providing good true scaled visual odometry estimation and recognition of indoor regions.
8. SLAM - Indoor positioning and wayfinding	Kunhoth, J., Karkar, A., Al-Maadeed, S., & Al-Ali, A. (2020). Indoor positioning and wayfinding systems: a survey. Human-centric Computing and Information Sciences, 10(1), 1-41.	Navigation systems help users access unfamiliar environments. Current technological advancements enable users to encapsulate these systems in handheld devices, which effectively increases the popularity of navigation systems and the number of users. In indoor environments, lack of Global Positioning System (GPS) signals and line of sight with orbiting satellites makes navigation more challenging compared to outdoor environments. Radio frequency (RF) signals, computer vision, and sensor-based solutions are more suitable for tracking the users in indoor environments.	This article provides a comprehensive summary of evolution in indoor navigation and indoor positioning technologies. In particular, the paper reviews different computer vision-based indoor navigation and positioning systems along with indoor scene recognition methods that can aid the indoor navigation. Navigation and positioning systems that utilize pedestrian dead reckoning (PDR) methods and various communication technologies, such as Wi-Fi, Radio Frequency Identification (RFID) visible light, Bluetooth and ultra-wide band (UWB), are detailed as well. Moreover, this article investigates and contrasts the different navigation systems in each category. Various evaluation criteria for indoor navigation systems are proposed in this work. The article

			concludes with a brief insight into future directions in indoor positioning and navigation systems.
9. SLAM - Human-device interaction	Zhang, H., & Ye, C. (2017). An indoor wayfinding system based on geometric features aided graph SLAM for the visually impaired. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 25(9), 1592-1604.	This paper presents a 6-degree of freedom (DOF) pose estimation (PE) method and an indoor wayfinding system based on the method for the visually impaired. The PE method involves two-graph simultaneous localization and mapping (SLAM) processes to reduce the accumulative pose error of the device. In the first step, the floor plane is extracted from the 3-D camera's point cloud and added as a landmark node into the graph for 6-DOF SLAM to reduce roll, pitch, and Z errors. In the second step, the wall lines are extracted and incorporated into the graph for 3-DOF SLAM to reduce X , Y , and yaw errors.	The method reduces the 6-DOF pose error and results in more accurate pose with less computational time than the state-of-the-art planar SLAM methods. Based on the PE method, a wayfinding system is developed for navigating a visually impaired person in an indoor environment. The system uses the estimated pose and floor plan to locate the device user in a building and guides the user by announcing the points of interest and navigational commands through a speech interface. Experimental results validate the effectiveness of the PE method and demonstrate that the system may substantially ease an indoor navigation task.
10. SLAM - Loop Closure technique	Sprickerhof, J., Nüchter, A., Lingemann, K., & Hertzberg, J. (2011). A heuristic loop closing technique for large-scale 6d slam. Automatika, 52(3), 199-222.	This paper presents a novel heuristic for correcting scan pose estimations after loop closing in SLAM using 3D laser scans. Contrary to state-of-the-art approaches, the built SLAM graph is sparse, and optimization is done without any iteration between the SLAM front and back end, yielding a highly efficient loop closing method.	Several experiments were carried out in an urban environment and evaluated against ground truth. The results are compared to other state of the art algorithms, proving the high quality, yet achieved faster by an order of magnitude.

11. SLAM - Navigation system	Mur-Artal, R., Montiel, J. M. M., & Tardos, J. D. (2015). ORB-SLAM: a versatile and accurate monocular SLAM system. IEEE transactions on robotics, 31(5), 1147-1163.	This paper presents ORB-SLAM, a feature-based monocular simultaneous localization and mapping (SLAM) system that operates in real time, in small and large indoor and outdoor environments. The system is robust to severe motion clutter, allows wide baseline loop closing and relocalization, and includes full automatic initialization. Building on excellent algorithms of recent years, we designed from scratch a novel system that uses the same features for all SLAM tasks: tracking, mapping, relocalization, and loop closing	. A survival of the fittest strategy that selects the points and keyframes of the reconstruction leads to excellent robustness and generates a compact and trackable map that only grows if the scene content changes, allowing lifelong operation. We present an exhaustive evaluation in 27 sequences from the most popular datasets. ORB-SLAM achieves unprecedented performance with respect to other state-of-the-art monocular SLAM approaches. For the benefit of the community, we make the source code public.
12. SLAM - navigation system indoor wayfinding for an electric wheelchair	Luces, J. V. S., Promsutipong, K., & Hirata, Y. (2020, January). Indoor Wayfinding for an Electric Wheelchair Based on Wi-Fi Fingerprinting Localization. In 2020 IEEE/SICE International Symposium on System Integration (SII) (pp. 513-518). IEEE.	In this research we propose a method to enable the device to navigate toward the user upon request by using onboard sensors and the existing Wi-Fi infrastructure. Specifically, we create a map with the Received Signal Strength Indicator (RSSI) of existing Wi-Fi access points (using a method called Fingerprinting). When a user requests an assistive device, the RSSI values at the user's position are sent to it, and the device determines the rough position of the user using a KNN algorithm.	Typical Fingerprinting methods are affected by infrastructural changes which alter the profile of RSSI values at each location. Therefore, we propose that the map is constantly updated while the device moves in order to avoid errors due to changes in the infrastructure. Through experiments we confirmed that the device could locate the position where the request originated with an error of 2.612 m, and it was able to navigate towards it.
13. SLAM obstacle detection	Marcin Zukowski1, Krzysztof Matus1, Dawid Kamienski2, Miroslaw Kondratiuk2, Leszek Ambroziak2, and Barbara Kuc2, SLAM and	In the paper a solution proposal for indoor navigation and obstacle detection problem in hospital environment for a humanoid that is 150 cm tall was	Considering the robot size, a common approach for mobile robots utilizing single 2D laser scanner or RGB+Depth camera is not applicable as vertical field of view of scans is too narrow to detect all obstacles. We

	obstacle detection for tall autonomous robotic medical assistant AIP Conference Proceedings 2029, 020085 (2018); https://doi.org/10.1063/1.5066547	presented. As a medical assistant, the robot is expected to autonomously move between hospital rooms with extra care about people safety. The overview of existing solutions was made, mostly focused on Simultaneous Localization and Mapping (SLAM) applications including human-aware algorithms.	proposed a hybrid system combining laser scanner, multiple cameras and distance sensors. The hardware architecture and software design in Robot Operating System (ROS) were presented. The
14. SLAM - Outdoor Localisation	Liu, R., Zhang, J., Chen, S., & Arth, C. (2019, October). Towards SLAM-based outdoor localization using poor GPS and 2.5 D building models. In 2019 IEEE International Symposium on Mixed and Augmented Reality (ISMAR) (pp. 1-7). IEEE.	In this paper, we address the topic of outdoor localization and tracking using monocular camera setups with poor GPS priors. We leverage 2.5D building maps, which are freely available from open-source databases such as OpenStreetMap. The main contributions of our work are a fast initialization method and a non-linear optimization scheme.	The initialization upgrades a visual SLAM reconstruction with an absolute scale. The non-linear optimization uses the 2.5D building model footprint, which further improves the tracking accuracy and the scale estimation. A pose optimization step relates the vision-based camera pose estimation from SLAM to the position information received through GPS, in order to fix the common problem of drift. We evaluate our approach on a set of challenging scenarios. The experimental results show that our approach achieves improved accuracy and robustness with an advantage in run-time over previous setups.

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Thank you

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