2 February 2021

RENAUDIN Valérie

Indoor positioning technologies

limitless creativity to model the complexity of cities and human gaits

Université Gustave Eiffel

A unique, atypical and pioneering University created in 2020 grouping

- 1 research institute
- 1 university
- 1 school of architecture
- 3 engineering schools

École d'architecture de la ville & des territoires Paris-Est

EIVP École des ingénieurs de la ville de Paris École supérieure du génie urbain

ENSG Géomatique

ESIEE PARIS

IFSTTAR

UPEM Université Paris-Est Marne-la-Vallée

TEAM GEOLOC

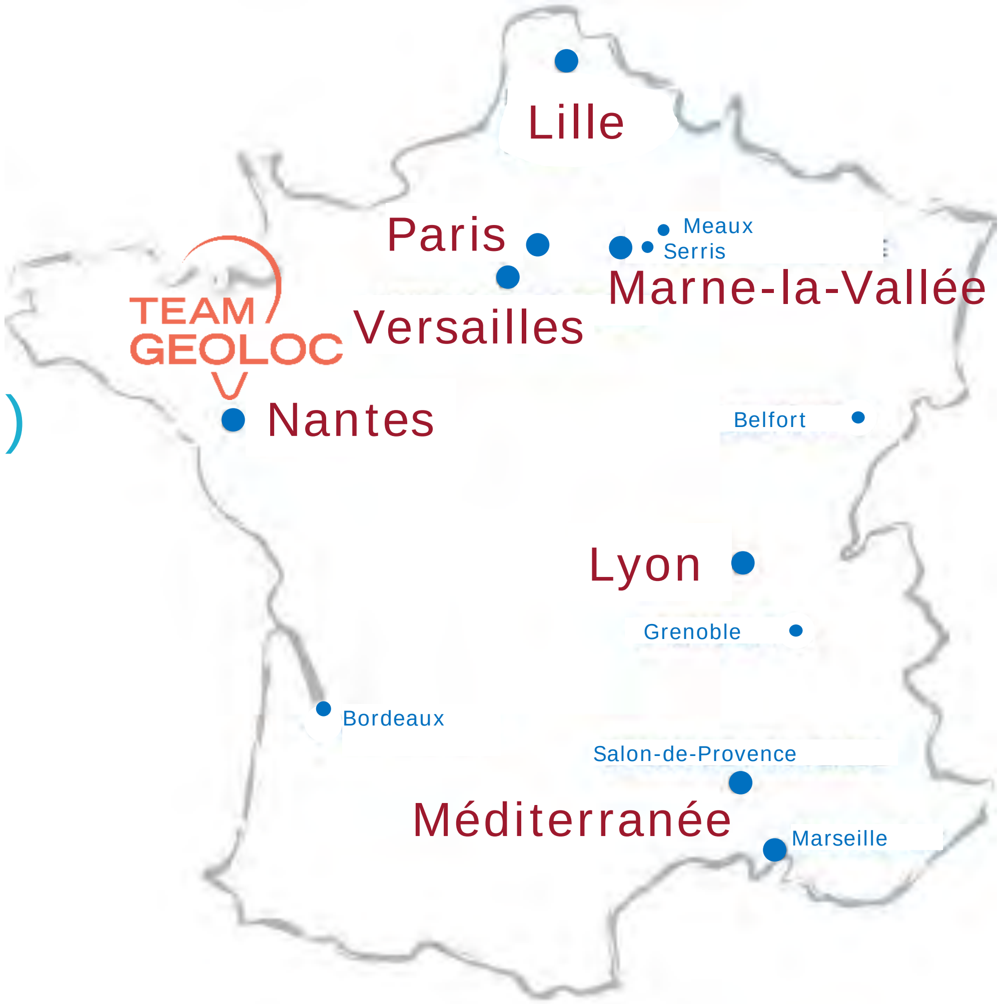
Université Gustave Eiffel

A National Multidisciplinary University...

2 associated institutes
2 associated schools
6 units of training and research (UFR)
6 institutes

23 research units: laboratories, teams, departments, institutes

7 Main campuses in France



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Positioning and navigation: a catalyst for new forms of mobility

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GEOLOC Research Activities

Geolocation at the service of the evolution of mobility

Ubiquitous positioning and navigation methods and systems

Evaluation and definition of positioning performance

NUMEROUS TECHNOLOGIES ARE PROPOSED TO MEET THE INDOOR CHALLENGES

SOME POPULAR INDOOR TECHNOLOGIES ON THE MARKET

Light Fidelity

Motion Detection

Facial Recognition

Smartphone

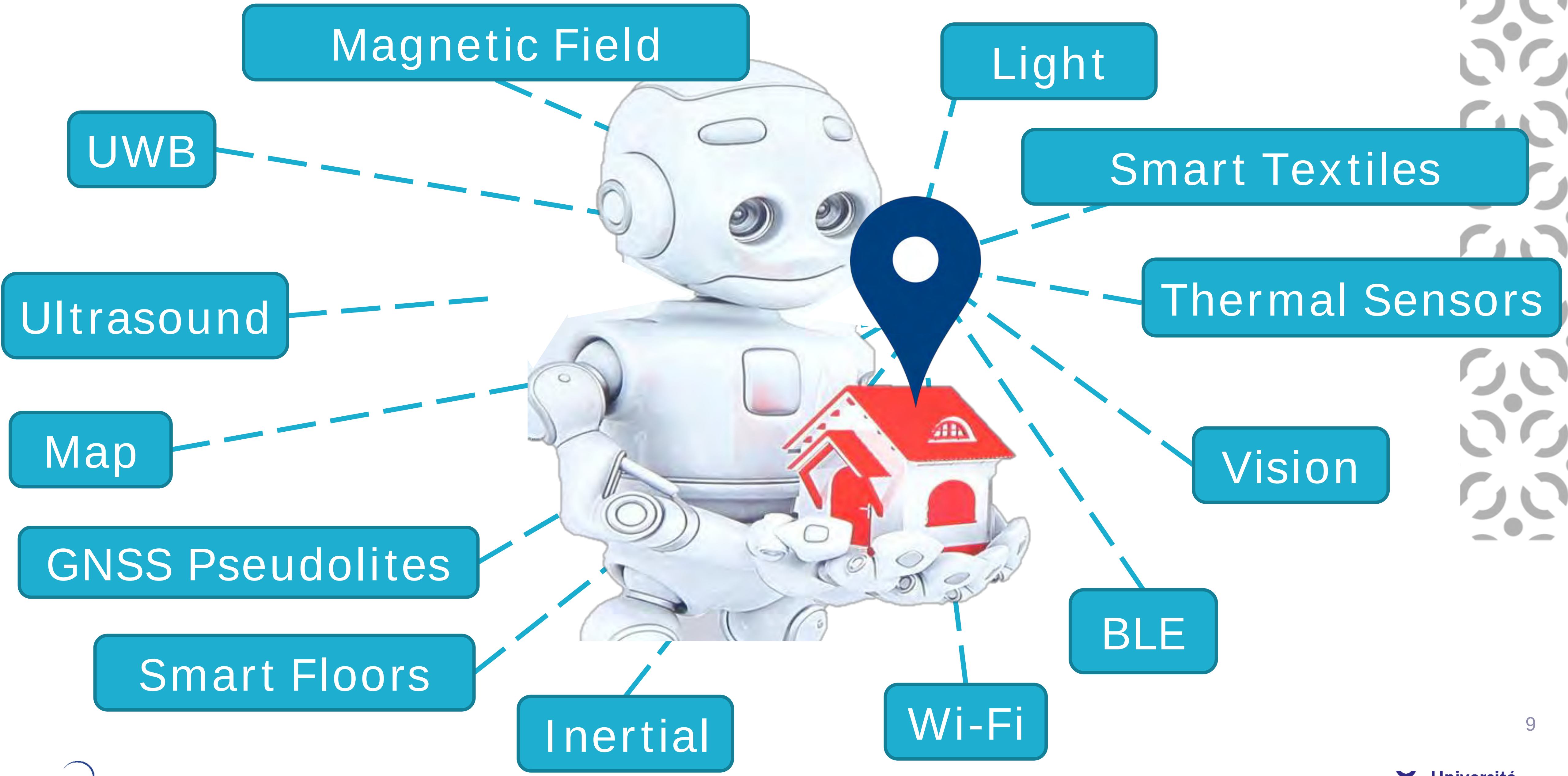
Vocal Assistant

Application Fields

- Comfort
- E-Health
- Safety and Security

Social Context

- General Public Adoption
- Minimized Cost
- Data Privacy


Magnetic Field
Light
UWB
Smart Textiles
Ultrasound
Thermal Sensors
Map
Vision
GNSS Pseudolites
BLE
Smart Floors
Inertial
Wi-Fi

self-contained technique

indoor infra-structure equipment

Indoor infrastructure equipment

Radio-propagation (WiFi, UWB, BLE, RFID)

Magnetic prints

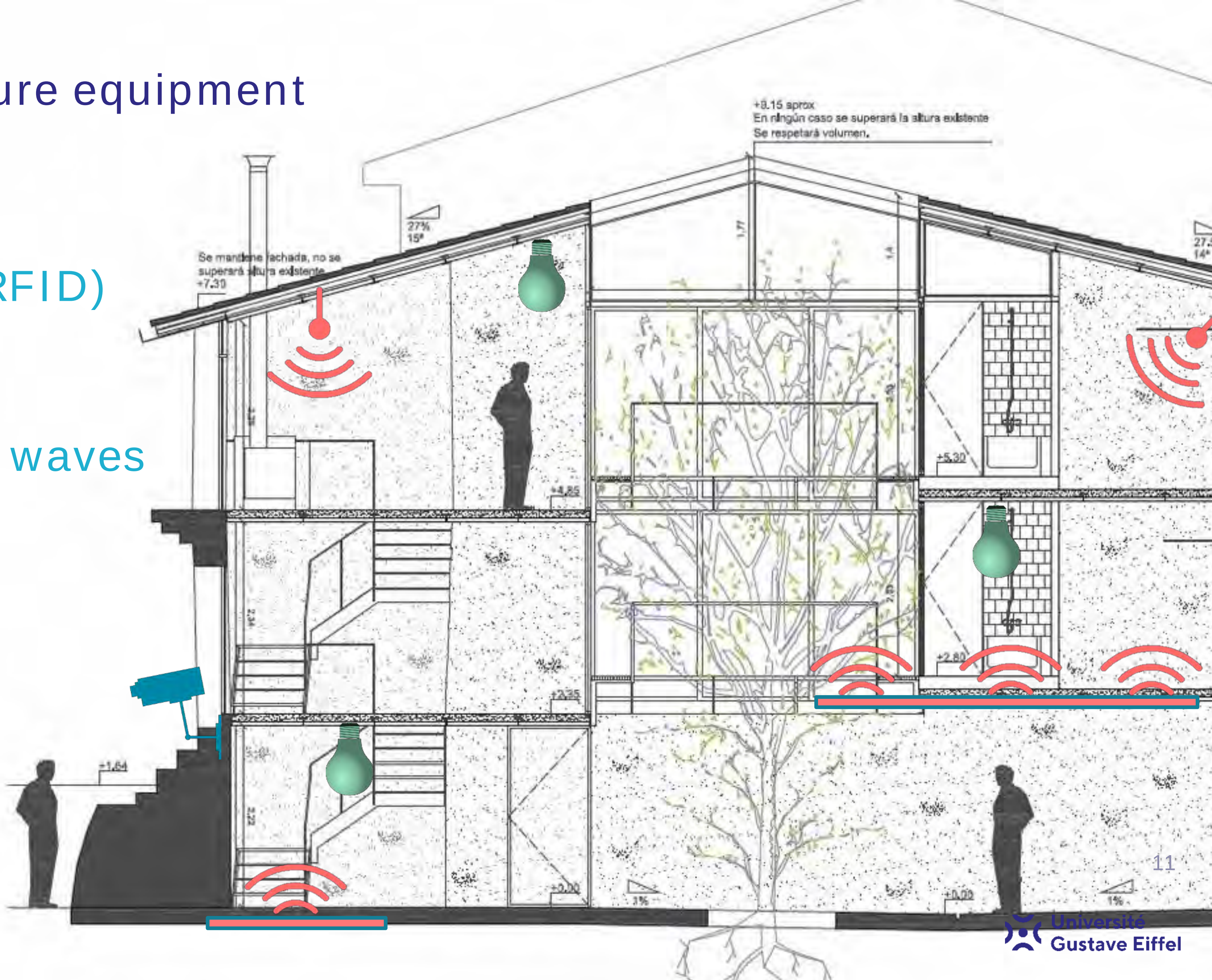
Ultrasound, sound waves

Vision, camera

Light

Thermal sensors

Smart floors



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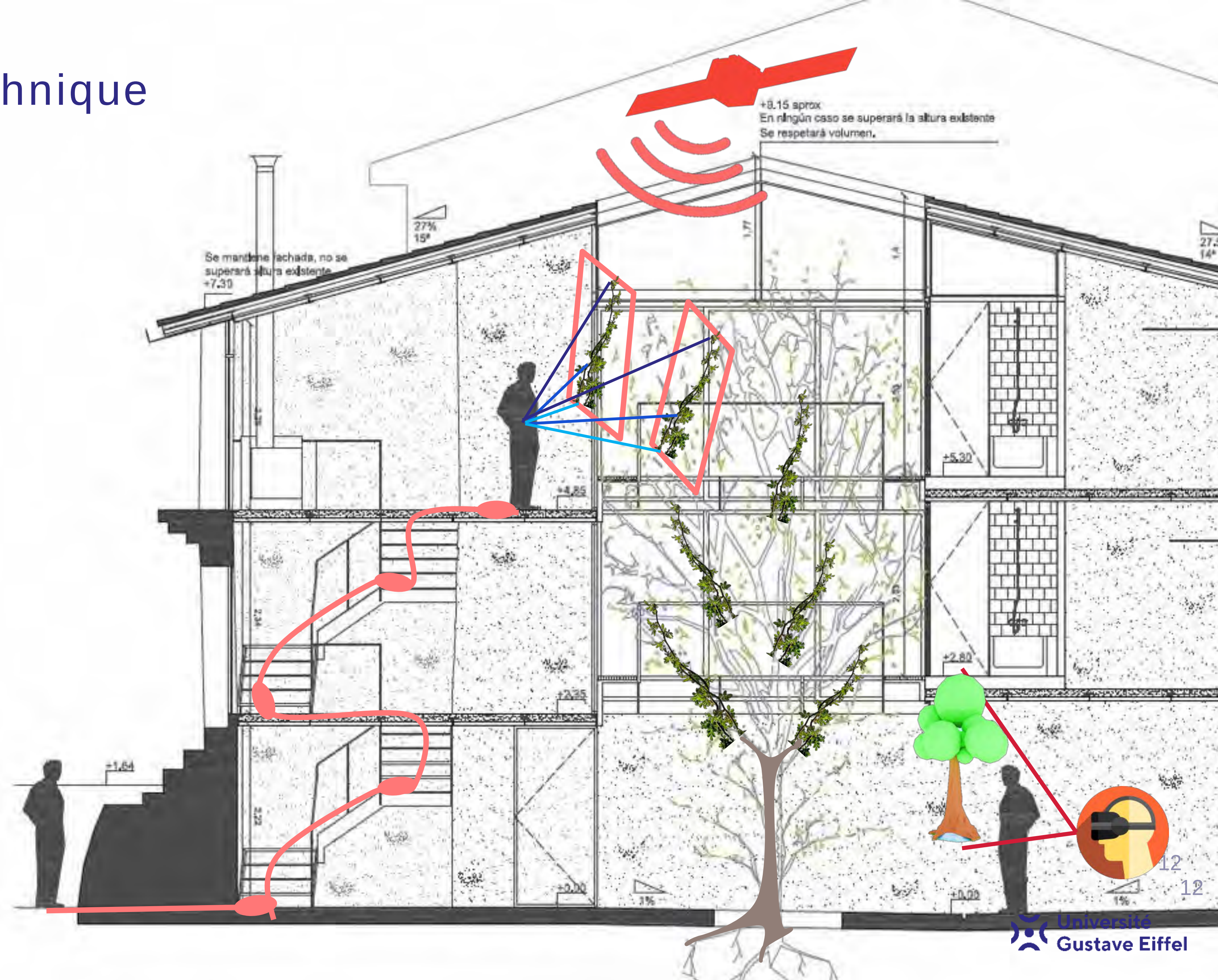
Self-contained technique

- Vision (VO, AR)
- Inertial sensors
- Magnetic field
- GNSS
- Smart textiles
- NB IOT - 5G



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Positioning Algorithms: Multiple Strategies

Despite decades of research, no universal solution has been adopted indoors

Seamless, ubiquitous and accurate positioning means sensor fusion

Difficulties to integrate all technologies. How to choose?

Sensor fusion is the key!

A question of criteria?

Infrastructure context
- Hardware already deployed for other reasons than « positioning »
- Need to be independent from the infrastructure (first responders)
- Pre-surveying indoor spaces
- Self learning process

Performance metrics
- Absolute/Relative accuracy
- Positioning or Tracking
- Steady signal propagation spaces

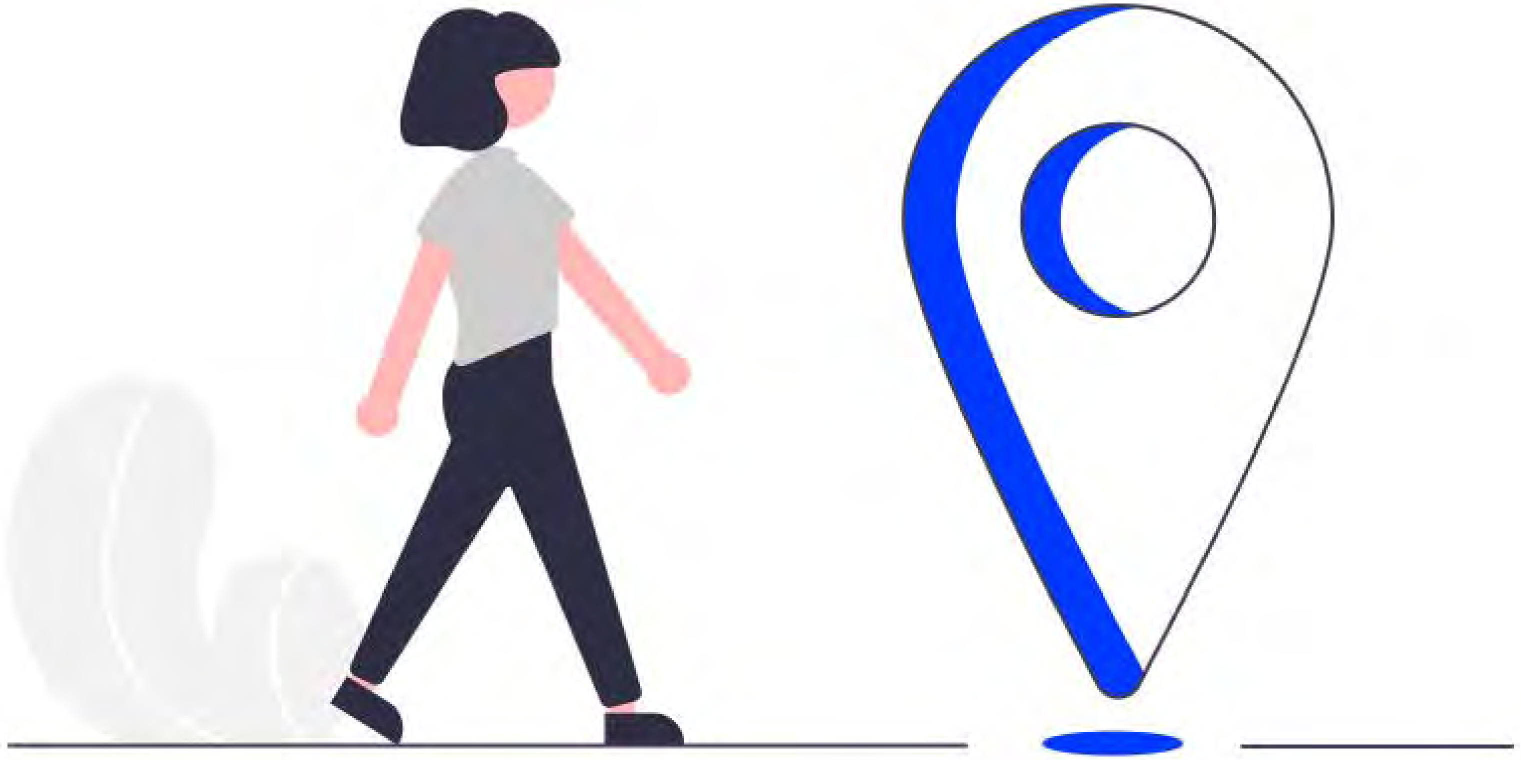
Cost
- Energy
- Installation, Maintenance
- Computation

Use case
- General Public / Professional Usage / Privacy
- Environmental and locomotion contexts
- Human in the loop?
- Integrity / Accuracy / Continuity / Smooth

Renaudin V, Dommes A and Guilbot M (2016), *"Engineering, human and legal challenges of navigation systems for personal mobility"*, IEEE Transaction on Intelligent Transportation Systems, pp. 177-191, 2016

Main sensor fusion strategies

Linear Quadratic Estimation	Sequential Monte Carlo	Learning Methods
• Kalman Filters, ... • Minimization of the quadratic error • Suitable for real time processing approach • Mature and easy to implement • Not suitable for integrating spatial constraints	• Particle Filter, ... • Non-linear state-space modelling by particles clouds corresponding to distribution • Easy integration of spatial and movement constraints • Significant computation costs	• Neural network, Decision tree, Clustering, Dimension reduction, LSTM, ... • Native approaches to classify / recognize context • Require large amounts of data • How to control data quality? Supervised/Unsupervised?



TESTING IN REAL LIFE CONDITIONS: A NECESSITY!

Renaudin V, Ortiz M, Perul J and al (2019), *"Evaluating Indoor Positioning Systems in a Shopping Mall: The Lessons Learned From the IPIN 2018 Competition"*, IEEE ACCESS, pp.148594-148628. Institute of Electrical and Electronics Engineers -- IEEE.

Potorti F, Park S, Crivello A, Palumbo F, Girolami M, Barsocchi P, Lee S, Torres-Sospedra J, Jimenez AR, Perez-Navarro A, Mendoza-Silva GM, Seco F, Ortiz M, Perul J, Renaudin V, and al., *"The IPIN 2019 Indoor Localisation Competition -Description and Results"*, IEEE Access, November, 2020, 47p. Institute of Electrical and Electronics Engineers (IEEE).

Indoor Positioning Challenge organized by the ANR and DGA in France

CHALLENGE MALIN

DGA and ANR launched the challenge MAîtrise de la Localisation Indoor (MALIN)

indoor positioning in non collaborative environment

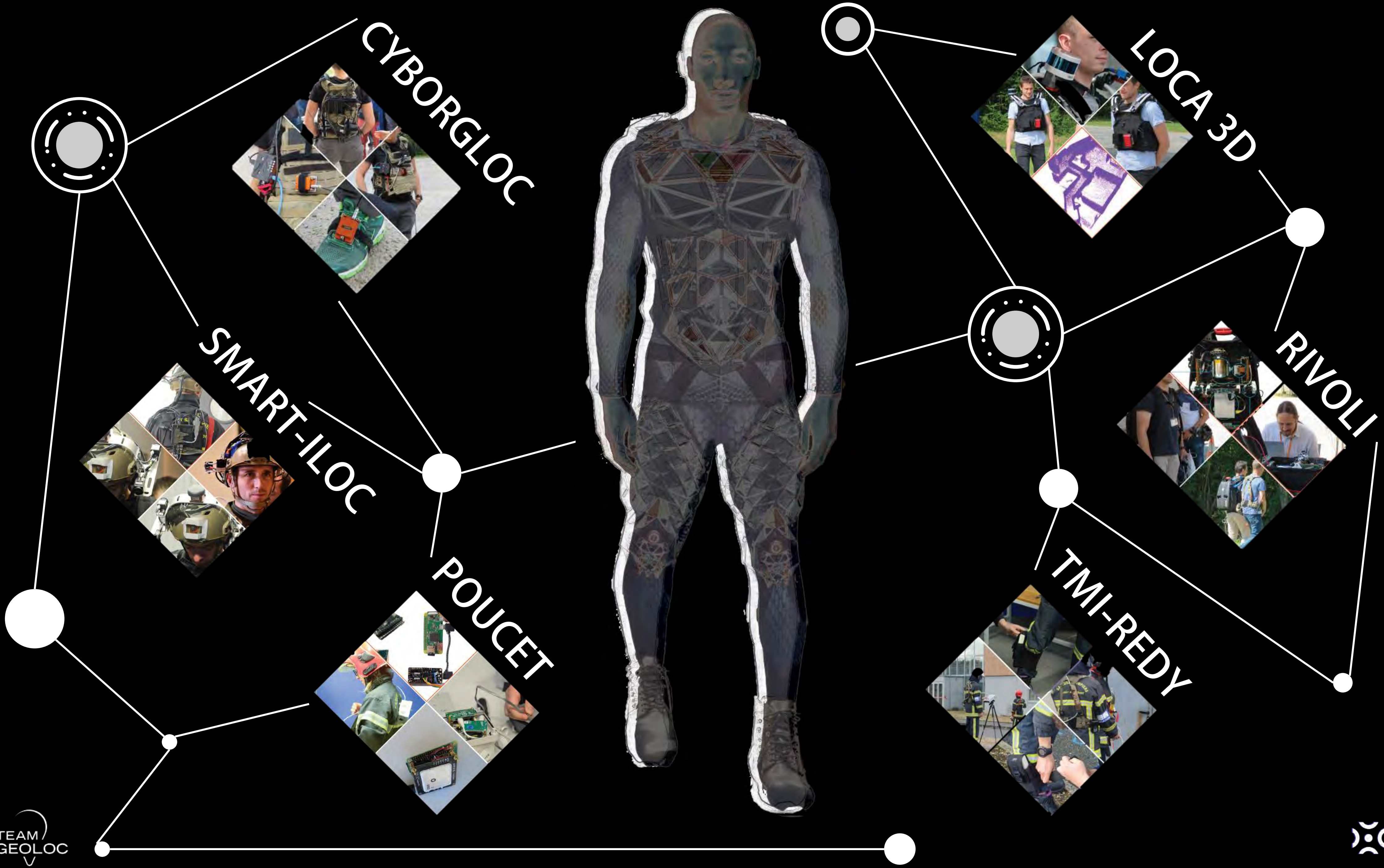
Objectives
- compare different architectures enabling the positioning of persons in complex environments such as buildings or undergrounds in the absence or partial availability of GNSS signals
- support innovation in the domain of autonomous positioning of soldiers and emergency response officers
- address the issue of Indoor-Outdoor transitions

2 Funding Bodies (ANR, DGA)

6 Teams

3 Competitions

2 Scenarios (Reference, Evaluation)


CYBORGLOC
LOCA 3D
SMART-ILOC
RIVOLI
POUCET
TMI-REDY

TEAM CYBORGLOC

Technologies

- For the positioning
  - Foot mounted inertial, magnetic field sensors
  - Barometer and GNSS on the torso
- For mapping
  - Camera on the shoulder

Hardware

Algorithms

Performances

CYBORGLOC: Hardware

GNSS M8N

Computing cluster

Stereo camera/ inertial Realsense D435i

Barometer

PERSY

Components and characteristics

Weight	< 300 g
Gyroscope drift	0,5 °/h
Accuracy of the estimated trajectory (% of the distance travelled)	0,3 %
STIM300 (Sensonor)	
Sampling Frequency	160 Hz
Triaxial accelerometer	
Triaxial gyroscope	
HMC5983 (Honeywell)	
Sampling Frequency	160 Hz
Triaxial magnetometer	
NEO-M8T (Ublox)	
Single-frequency, dual-constellation GNSS receiver	5 Hz
SD card	
Battery	
Battery life	4 hours

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Positioning algorithms: a classical strapdown inertial navigation approach

Evolution of the velocity ($\dot{\mathbf{x}}$) of the mobile in time

$$\forall u \in [t, \Delta t]$$

$$\dot{\mathbf{x}}_{t+\Delta t}^{\mathrm{n}} = \int_{t}^{t+\Delta t} \ddot{\mathbf{x}}^{\mathrm{n}}\, du = \dot{\mathbf{x}}_{t}^{\mathrm{n}} + \ddot{\mathbf{x}}^{\mathrm{n}}\, \Delta t$$

Evolution of the position ($\mathbf{x}$) of the mobile in time

$$\forall u \in [t, \Delta t]$$

$$\mathbf{x}_{t+\Delta t}^{\mathrm{n}} = \int_{t}^{t+\Delta t} \dot{\mathbf{x}}^{\mathrm{n}}\, du = \mathbf{x}_{t}^{\mathrm{n}} + \dot{\mathbf{x}}_{t}^{\mathrm{n}} \Delta t + \frac{1}{2} \ddot{\mathbf{x}}^{\mathrm{n}}\, \Delta t^{2}$$

With only an accelerometer bias error modeling

$$\ddot{\mathbf{x}} = \mathbf{f} - \mathbf{g} - \mathbf{b}_f + \mathbf{w}_f$$

$\mathbf{g}$ is known in the local geographical frame and $\mathbf{f}$ is measured in the inertial sensors frame → How to estimate the orientation ?

Positioning algorithms: estimating the orientation with quaternions

Acceleration in the local frame

$$(0, \ddot{\mathbf{x}}^{\mathrm{n}}) = \mathbf{q}_{\mathrm{b}}^{\mathrm{n}} \circ \left(0, \ddot{\mathbf{x}}^{\mathrm{b}}\right) \circ \overline{\mathbf{q}}_{\mathrm{b}}^{\mathrm{n}} - (0, \mathbf{g}^{\mathrm{n}})$$

Evolution of the attitude angles quaternion

$$\mathbf{q}_{\mathrm{b}}^{\mathrm{n}}(t + \Delta t) = \mathbf{q}_{\mathrm{b}}^{\mathrm{n}}(t) \circ \mathbf{q}_{\omega}^{\mathrm{b}}(t)$$

Relation between quaternion and angular rates

$$\mathbf{q}_{\omega}^{\mathrm{b}}(t) = \begin{pmatrix} \cos\left(\frac{\|\boldsymbol{\omega}_{\mathrm{nb}}^{\mathrm{b}}\|}{2} \Delta t\right) \\ \sin\left(\frac{\|\boldsymbol{\omega}_{\mathrm{nb}}^{\mathrm{b}}\|}{2} \Delta t\right) \frac{\boldsymbol{\omega}_{\mathrm{nb}}^{\mathrm{b}} \Delta t}{\|\boldsymbol{\omega}_{\mathrm{nb}}^{\mathrm{b}} \Delta t\|} \end{pmatrix} + \mathbf{w}_{q_{\omega}}^{\mathrm{b}}$$

With only a gyroscope bias error modeling

$$\boldsymbol{\omega} = \boldsymbol{\omega} + \mathbf{b}_{\omega} + \mathbf{w}_{\omega}$$

Positioning algorithms: mitigating **gyroscopes’** error with magnetometer

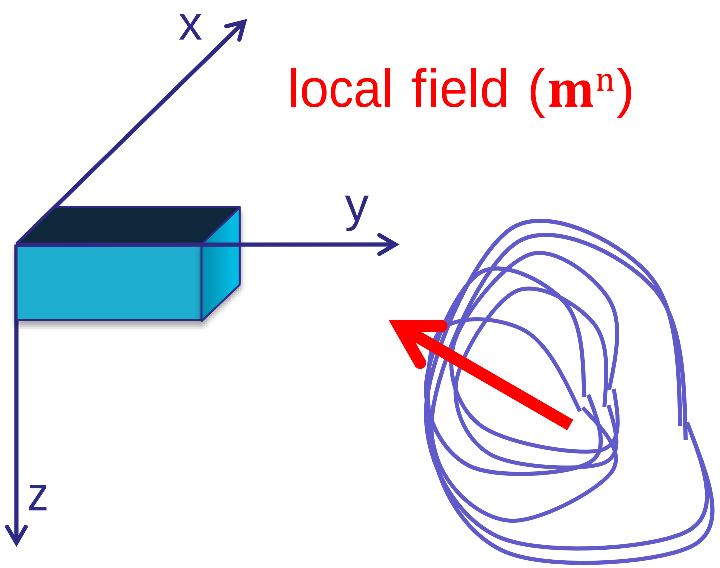
When the local magnetic field is static, even indoors, 2 corrections are possible

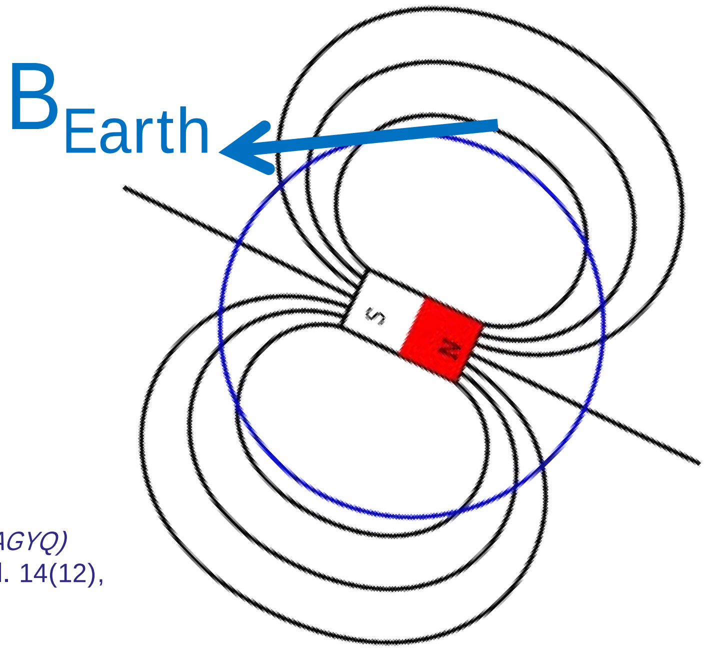
Quasi Static Field Update

All measured magnetic field in the local map frame are the same

Magnetic Angular Rate Update

Quaternions derived from the magnetic and gyroscope angular rates over a same period are the same





Renaudin V and Combettes C (2014), *"Magnetic, Acceleration Fields and Gyroscope Quaternion (MAGYQ) Based Attitude Estimation with Smartphone Sensors for Indoor Pedestrian Navigation"*, Sensors. Vol. 14(12), pp. 22864-22890.

Positioning algorithms: mitigating the propagation of accelerometer errors

Biomechanics features in walking gait captured by foot mounted

Main principle: during the stance phase, the foot velocity equals zero

$$\dot{\mathbf{x}}^{\mathrm{n}} = \mathbf{0}$$

Zero Velocity Update

Observation Equations: δ is the perturbation of the state

$$\begin{bmatrix} 0 \\ \delta\dot{\mathbf{x}}^{\mathrm{n}} \end{bmatrix} = \mathbf{q}_{\mathrm{b}}^{\mathrm{n}} \circ [0 \quad (\mathbf{f}^{\mathrm{n}} - \mathbf{b}_{\mathrm{f}}^{\mathrm{n}})^T]^T \circ (\mathbf{q}_{\mathrm{b}}^{\mathrm{n}})^{-1}\delta t + \begin{bmatrix} 0 \\ \mathbf{g}^{\mathrm{n}} \end{bmatrix} \delta t$$

$$\begin{bmatrix} 0 \\ \delta\mathbf{x}^{\mathrm{n}} \end{bmatrix} = \dot{\mathbf{x}}^{\mathrm{n}}\delta t + \frac{\mathbf{q}_{\mathrm{b}}^{\mathrm{n}}}{2} \circ [0 \quad (\mathbf{f}^{\mathrm{n}} - \mathbf{b}_{\mathrm{f}}^{\mathrm{n}})^T]^T \circ (\mathbf{q}_{\mathrm{b}}^{\mathrm{n}})^{-1}\delta t^2 + \begin{bmatrix} 0 \\ \mathbf{g}^{\mathrm{n}} \end{bmatrix} \delta t^2$$

Le Scornec J, Ortiz M and Renaudin V (2017), *"Foot-mounted pedestrian navigation reference with tightly coupled GNSS carrier phases, inertial and magnetic data"*, In 2017 International Conference on Indoor Positioning and Indoor Navigation (IPIN). Sapporo, Japan, September, 2017

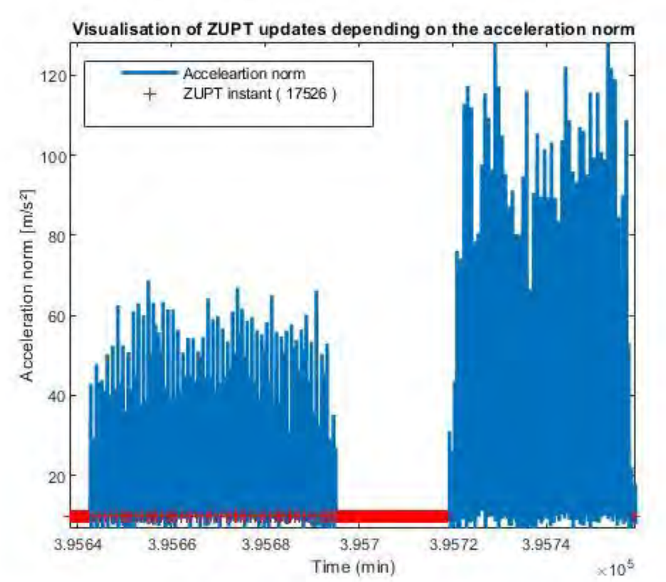
Positioning algorithms: correctly detecting zero velocity instants

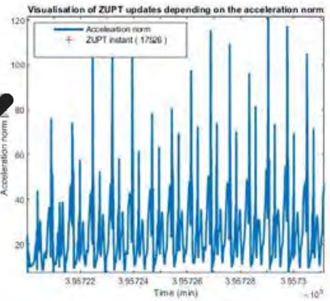
Main principals of zero velocity detectors

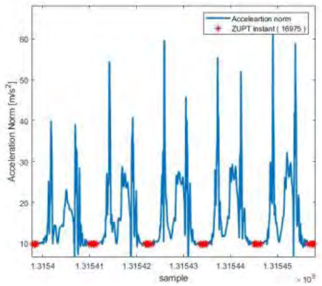
- Use of activity thresholds
- Adopt time windows based analysis for real time application
- Process signals statistics: variance, norm, frequency components, etc.

Problems

- How to fix all thresholds? How to adapt to different motions/ humans? Which window sizes?







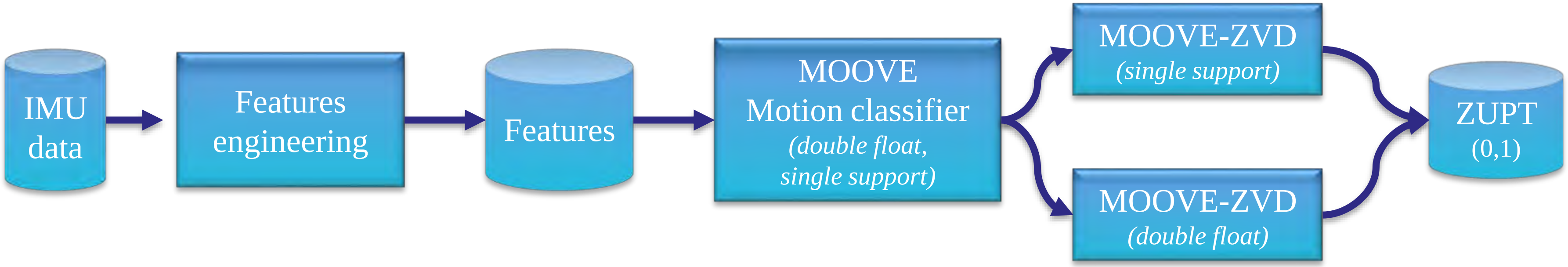
Zhu N, Ortiz M, Renaudin V, Ichard C and Ricou S (2021), *"Dataset of the intermediate competition in challenge MALIN: Indoor–outdoor inertial navigation system data for pedestrian and vehicle with high accuracy references in a context of firefighter scenario"*, Data in Brief, feb, 2021. Vol. 34, pp. 106626. Elsevier

Positioning algorithms: correctly detecting zero velocity instants

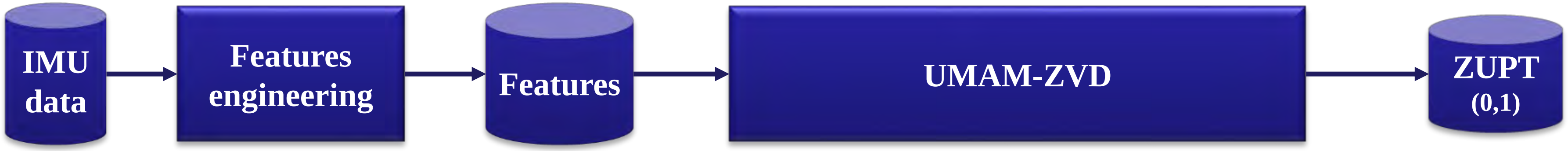
Adopting machine learning to detect a large variety of human dynamics

Creation of 2 models using hist gradient boosting approach

Mixed AI mOdels with mOVement prE-classification (MOOVE)



Uniform AI Model for All pedestrian Motions (UMAM)



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Koné Y, Zhu N, Renaudin V and Ortiz M (2020), *"Machine Learning--Based Zero--Velocity Detection for Inertial Pedestrian Navigation"*, IEEE Sensors Journal, 11p. Institute of Electrical and Electronics Engineers -- IEEE.

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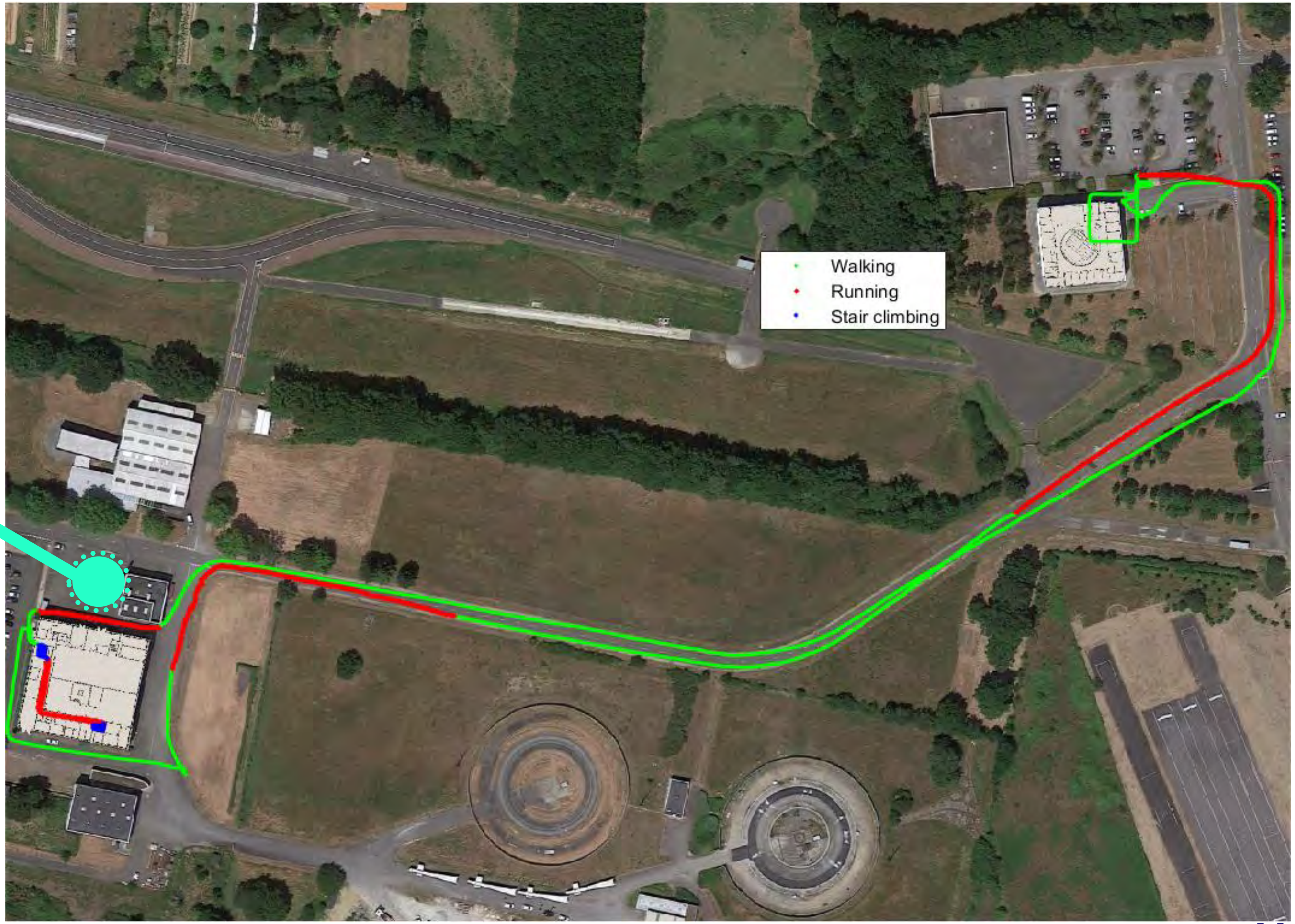
Positioning algorithms: correctly detecting zero velocity instants



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Positioning algorithms: 2 complementary filters

Altitude filter

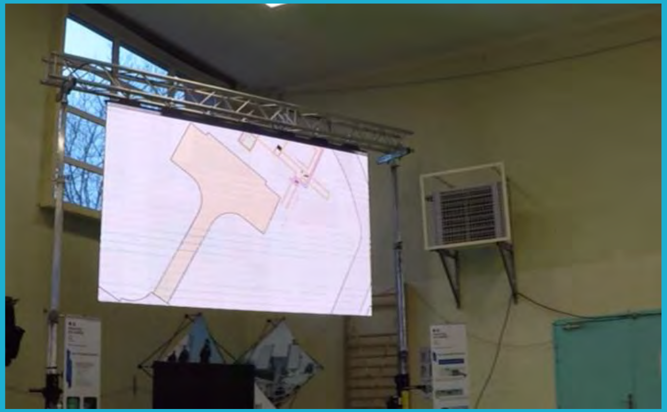
- Use of barometer data to correct the estimated altitude:
  T_{ref} , P_{ref} temperature and pression of reference, h_t is the altitude at time t
  L, R and g_0 are fixed variables

$$\delta h_t^{\mathbf{n}} = -\frac{T_{ref}}{L}\left(1-\left(\frac{P}{P_{ref}}\right)^{\frac{-LR}{g_0}}\right) - h_{t_0 t}^{\mathbf{n}}$$

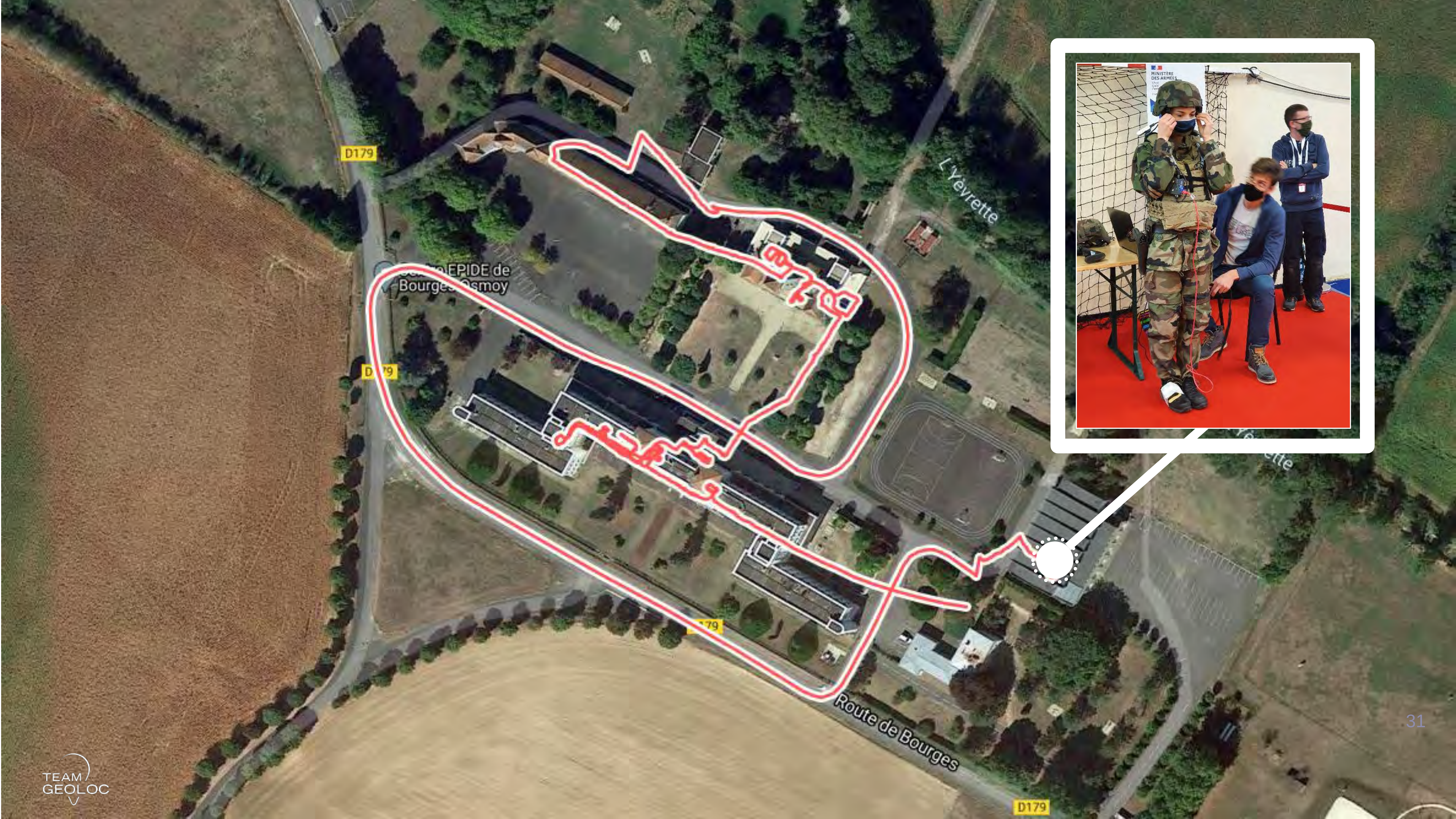
Rotation/Translation filter

- To mitigate misalignment issues between the inertial unit mounted on the foot and the walking direction (Rotation, Translation)
- Estimation of optimal 2D similarity between a track estimated by GPS signals and the track estimated by inertial and magnetic field signals
- Loose coupling introduces potential issues related to Non Line of Sight signals → Tight coupling

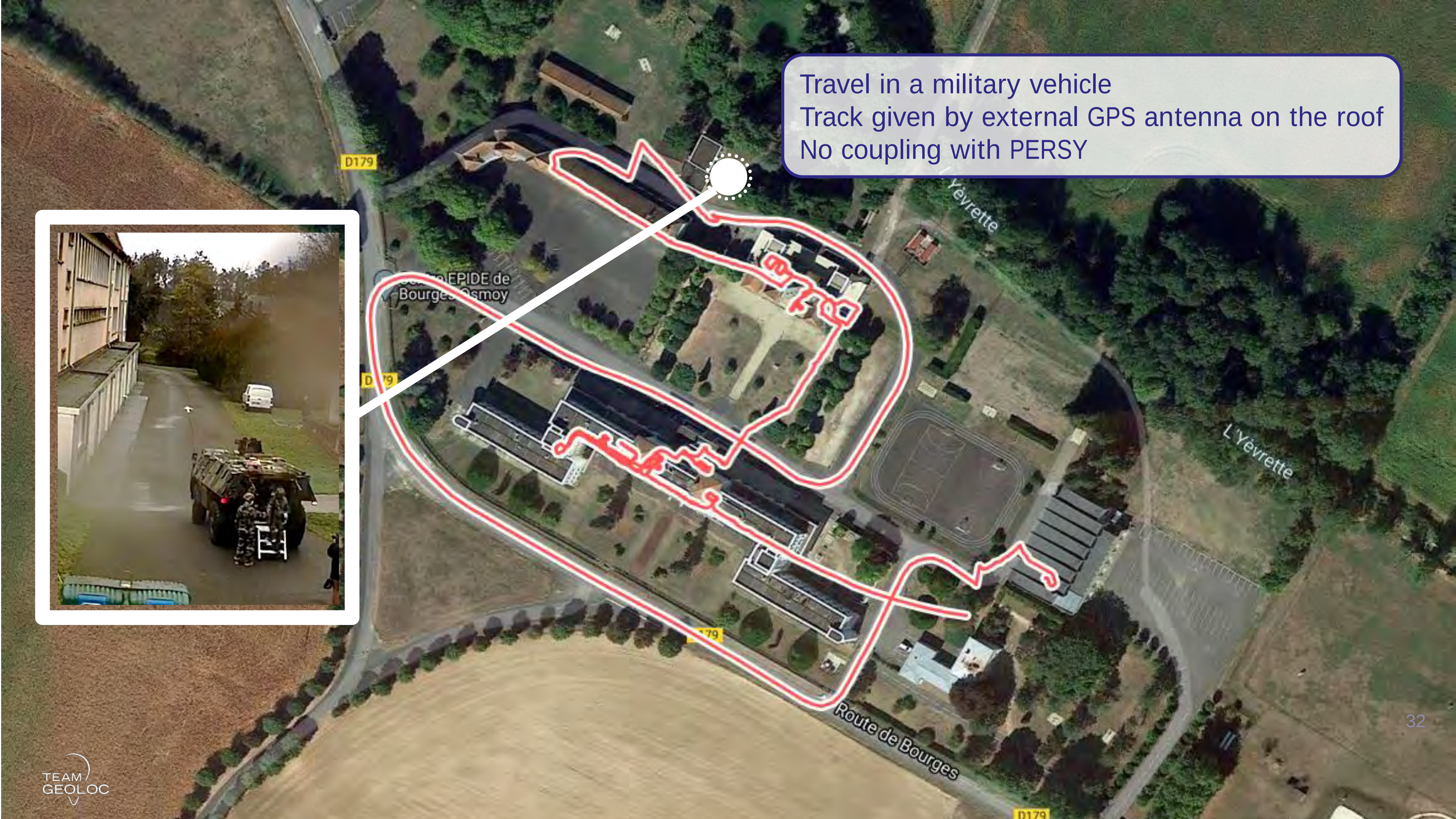



Thursday 27: Evaluation Scenario
with real time display of the track on a large screen


D179
EPIDE de
Bourge
smoy
L'Yèvrette
Route de Bourges
MINISTÈRE DES ARMÉES

Travel in a military vehicle
Track given by external GPS antenna on the roof
No coupling with PERSY



Entering into the building
Rotation/Translation correction with GPS outdoor
3m positioning error

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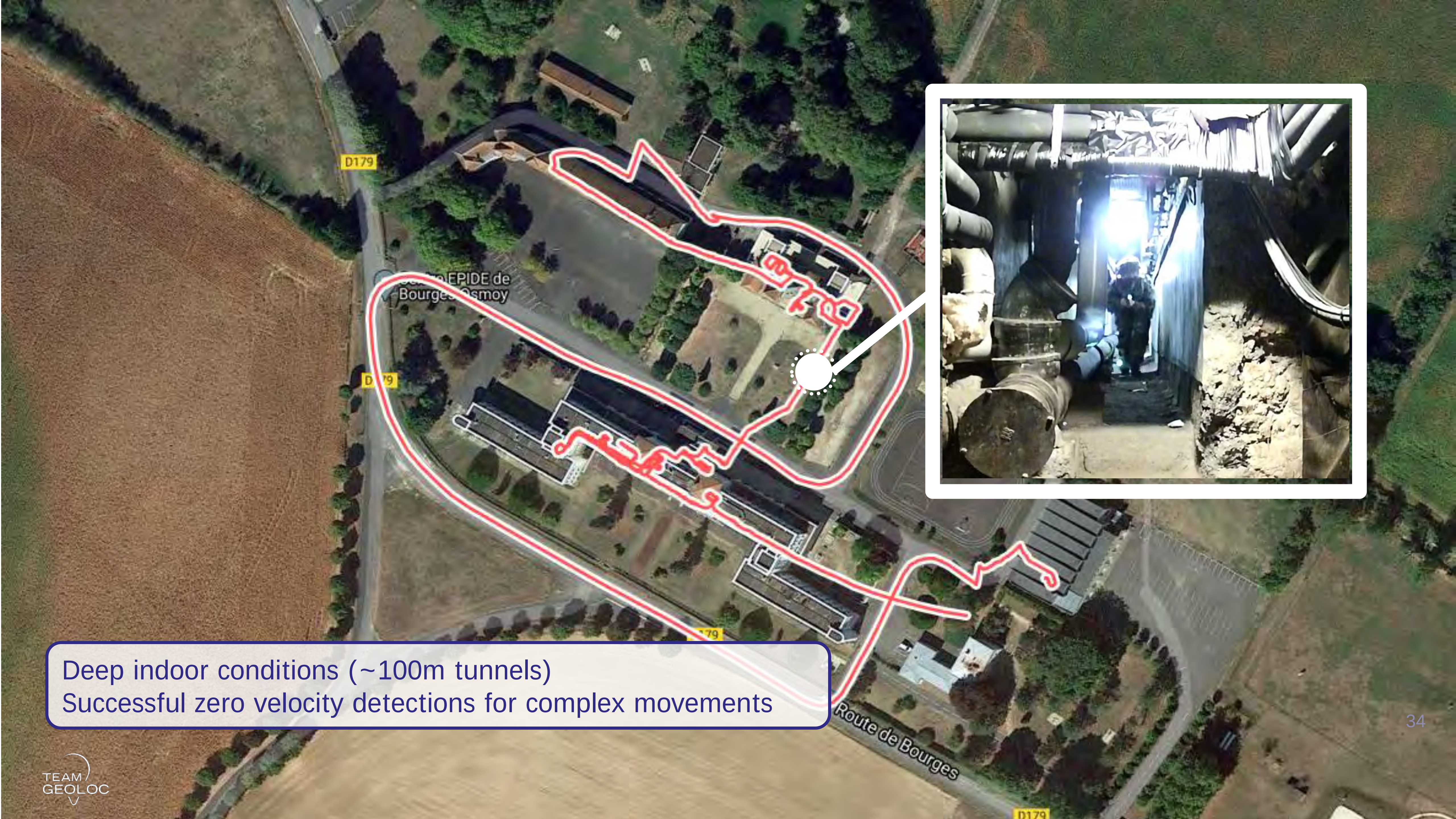

Deep indoor conditions (~100m tunnels)
Successful zero velocity detections for complex movements

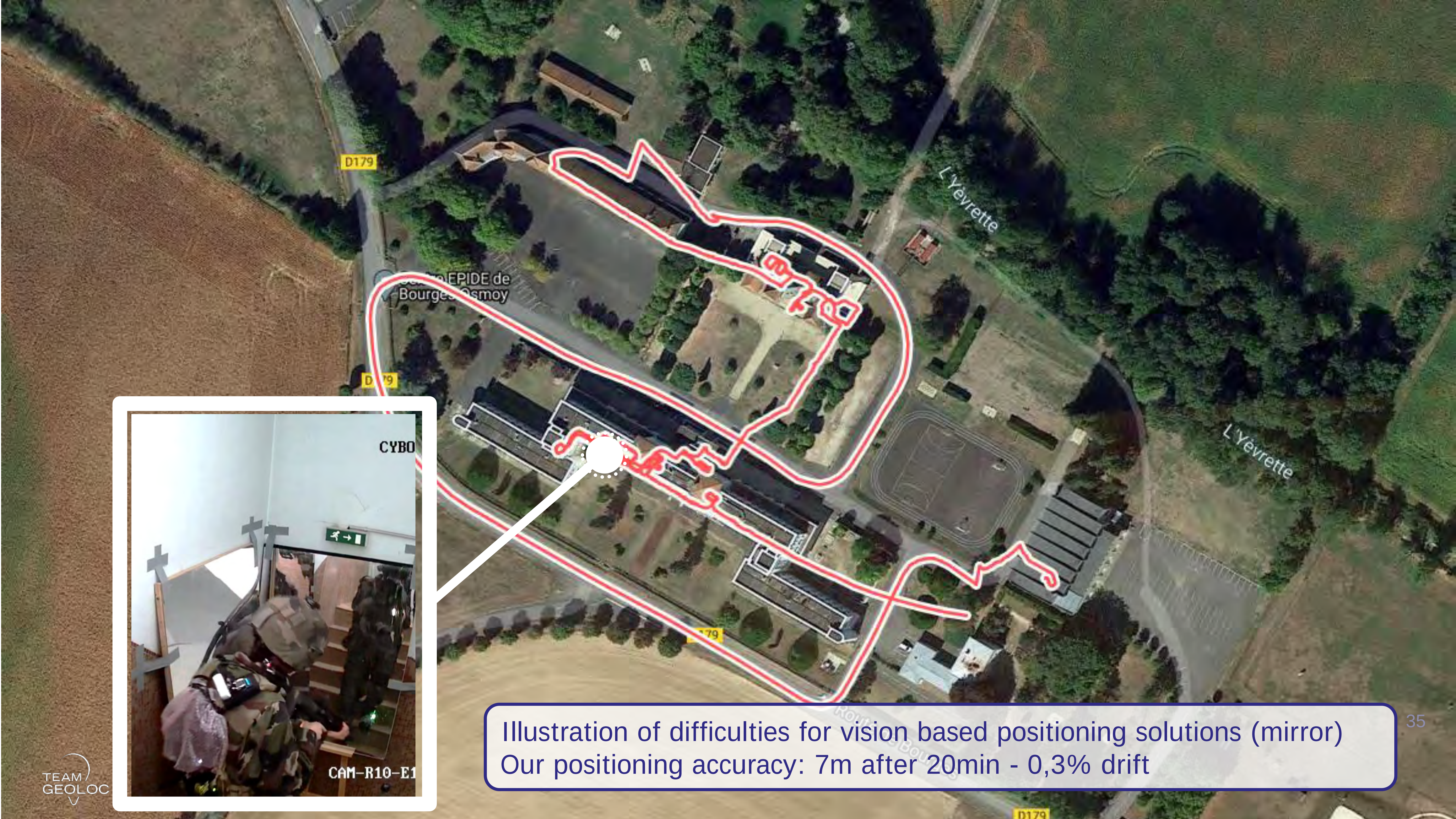

Illustration of difficulties for vision based positioning solutions (mirror)
Our positioning accuracy: 7m after 20min - 0,3% drift

No zero velocity period detected during crawling
Motion not learned in the machine learning models
Coordinates estimation stopped intentionally (outliers)!

Dead reckoning only positioning solution is still working (green)

Increased difficulty: movement on a treadmill

Proprioceptive inertial measures on legs are uncorrelated with the pedestrian’s position estimates

TO CONLUDE: SOME KEY FIGURES OF OUR ACHIEVMENT IN SHORT

2.5 km
Total traveled distance (without the vehicle part)

45 min
Duration

4 levels
3 floors & 1 underground

9 mvt
waling, running, stairs climbing/backward descending, crawling, ladder, side stepping, treadmill, tour on itself

0.3 % positioning error over the total traveled distance >> Well above state of the art performances, especially in harsh conditions

Classical indoor positioning performance of dead reckoning 1 - 0.5%, evaluated on short distances (~100 m), simple movements

Inertial, magnetometers and barometers positioning solutions are found to be more robust than vision based solutions

Artificial intelligence implemented in real-time has successfully enabled the integration of a wide variety of human gait movements → Understanding the physics is key!

Our solution was in the top 2 of the final competition (the most challenging one)!

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