# Gaussian Process Preintegration for Inertial-Aided Navigation Systems

**by Cedric Le Gentil**

Thesis submitted in fulfilment of the requirements for the degree of

**Doctor of Philosophy**

under the supervision of A/Prof. Teresa Vidal-Calleja and A/Prof. Shoudong Huang

University of Technology Sydney
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# Certificate of Original Authorship

I, Cedric Le Gentil declare that this thesis, is submitted in fulfilment of the requirements for the award of degree of Doctor of Philosophy, in the Faculty of Engineering and IT (FEIT) at the University of Technology Sydney (UTS).

This thesis is wholly my own work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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# *Abstract*

To perform any degree of autonomy, a system needs to localise itself, generally requiring knowledge about its environment. While satellite technologies, like GPS or Galileo, allow individuals to navigate throughout the world, the level of accuracy of such systems, and the necessity to have a direct view of the sky, do not match the precision and robustness requirements needed to deploy robots in the real world. To overcome these limitations, roboticists developed localisation and mapping algorithms traditionally based on camera images or radar/LiDAR data. Across the last two decades, Inertial Measurement Units (IMUs) became ubiquitous. Thus, LiDAR-inertial and visual-inertial pose estimation algorithms represent now the majority of the state estimation literature.

Preintegration became a standard method to aggregate inertial measurement units (IMUs) readings into pseudo-measurements for navigation systems. This thesis presents a novel preintegration theory that leverages data-driven continuous representations of the inertial data to perform analytical inference of the signal integrals. The proposed method probabilistically infers the pseudo-measurements, called *Gaussian Preintegrated Measurements* (GPMs), over any time interval, using Gaussian Process (GP) regression to model the IMU measurements and leveraging the application of linear operators to the GP covariance kernels. Thus, the GPMs do not rely on any explicit motion-model.

This thesis presents two inertial-aided systems that leverage the GPMs in offline batch-optimisation algorithms. The first one is a framework called IN2LAAMA for *INertial Lidar Localisation Autocalibration And MApping*. The proposed method addresses the issue of *motion distortion* present in most of today's LiDARs' data thoroughly by using GPMs for each of the LiDAR points.

The second GPM application is an event-based visual-inertial odometry method that uses lines to represent the environment. Event-cameras generate highly asynchronous streams of events that are individually triggered by each of the camera pixels upon illumination changes. Our framework, called IDOL for *IMU-DVS Odometry using Lines*, estimates the system's pose as well as the position of 3D lines in the environment by considering the camera events in the framework's cost function individually (no aggregation in image-like data). The GPMs allow for the continuous characterisation of the system's trajectory, therefore accommodating the asynchronous nature of event-camera data.

Extensive benchmarking of the GPMs is performed on simulated data. The performance of IN2LAAMA is thoroughly demonstrated throughout simulated and real-world experiments, both indoor and outdoor. Evaluations on public datasets show that IDOL performs at the same order of magnitude as current frame-based state-of-the-art visual-inertial odometry frameworks.

*"Vous savez, moi je ne crois pas qu'il y ait de bonne ou de mauvaise situation. Moi, si je devais résumer ma vie aujourd'hui avec vous, je dirais que c'est d'abord des rencontres."*[1]

Édouard Beaer

[1] "Well, you see... I don't believe that there are good or bad situations. If I had to summarise my life, here, with you, I would say that it is all about encounters."

# *Acknowledgements*

The first person I want to thank is someone that I forgot the name of. When people ask me how I started my PhD, I refer to him as the "Spanish dude". During a smoko[2] on a building site in April 2016, I told him that I was thinking to quit my labourer job and attempt to volunteer in random software companies to try to "get back in my field". To this, he pronounced words that profoundly changed my life:

*"Why don't you go see a university for that?".*

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[2] Australian slang term designating a short break during work. Mostly used in the construction industry.

# Contents

# Acronyms & Abbreviations

| | |
|---|---|
| **1D** | One-Dimensional |
| **2D** | Two-Dimensional |
| **3D** | Three-Dimensional |
| **CAS** | Centre for Autonomous Systems |
| **CPU** | Central Processing Unit |
| **DoF** | Degree-of-Freedom |
| **DVS** | Dynamic Vision Sensor |
| **EKF** | Extended Kalman filter |
| **FoV** | Field-of-View |
| **GNSS** | Global Navigation Satellite System |
| **GP** | Gaussian Process |
| **GPM** | Gaussian Preintegrated Measurement |
| **GPS** | Global Position System |
| **GPU** | Graphic Processing Unit |
| **HDR** | High Dynamic Range |
| **ICP** | Iterative Closest Point |
| **IDOL** | IMU-DVS Odometry using Lines |

| | |
|---|---|
| **IMU** | Inertial Measurement Unit |
| **IN2LAAMA** | INertial Lidar Localisation Autocalibration And MApping |
| **KF** | Kalman Filter |
| **LiDAR** | Light Detection And Ranging Sensor |
| **LPM** | Linear Preintegrated Measurement |
| **MAP** | Maximum A Posteriori |
| **MLE** | Maximum Likelihood Estimation |
| **NDT** | Normal Distribution Transform |
| **PM** | Standard Preintegrated Measurement |
| **RRBT** | Rapidly Exploring Random Belief Trees |
| **RGB** | Red-Green-Blue |
| **RGBD** | Red-Green-Blue-Depth |
| **RMS** | Root Mean Squared |
| **RMSE** | Root Mean Squared Error |
| **SE(3)** | Special Euclidean group in three dimensions |
| **SLAM** | Simultaneous Localisation And Mapping |
| $\mathfrak{so}(3)$ | Lie algebra of special orthonormal group in three dimensions |
| **SO(3)** | Special orthonormal group in three dimensions |
| **UPM** | Upsampled-Preintegrated-Measurement |
| **UTS** | University of Technology, Sydney |
| **VI** | Visual-Inertial |
| **VIO** | Visual-Inertial Odometry |
| **VO** | Visual Odometry |