Satellite Pose Estimation via Consensus on Manifolds

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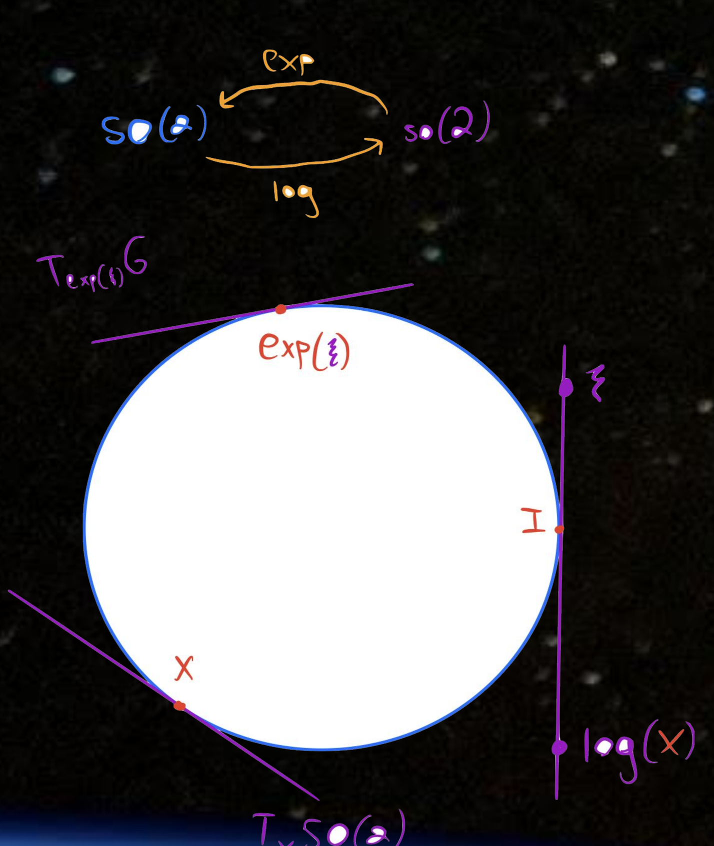
Consensus algorithms are a ubiquitous tool for multi-agent systems and distributed estimation. However, consensus algorithms are usually applied to vector spaces. For many applications, it is more natural to utilize the manifold structure of the system, such as the space of 3D rotations, than linearizing about a point. We combine an intrinsic consensus algorithm with ML-based pose estimations of an uncooperative satellite via a network of orbiting camera-equipped satellites. We trained a CNN on synthesized data from photorealistic simulator built in UE.

Review of Manifolds

	Vector Space	Manifolds (ex. SO(3))
Distance (squared)	$d^2(x,y) = \|x - y\|_2^2$	$d^2(x,y) = \min_{\{\gamma(\cdot)\in M:\gamma(0)=x,\gamma(1)=y\}} L(\gamma)$
Relative displacement	$x - y$	$\log_y(x)$
Average	$\arg\min_{x\in M} \sum_{i=1}^{N} d^2(x,x_i) = \frac{1}{N}\sum_{i=1}^{N} x_i$	$\arg\min_{x\in M} \sum_{i=1}^{N} d^2(x,x_i)$ (no closed form)
Consensus protocol	$x(k+1) = Wx(k)$ $W = I - \epsilon L$	$x(k+1) = \nabla\varphi(x) - \alpha y(k)$ $y(k+1) = \mathcal{T}_{x(k)}^{x(k+1)} W y(k) + \nabla\varphi(x(k+1)) - \nabla\mathcal{T}_{x(k)}^{x(k+1)}\varphi(x(k))$ $\varphi(x) = \frac{1}{2}\sum_{(i,j)\in E} d^2(x_i,x_j)$
Point of convergence	The Euclidean average	Riemannian center of mass



The manifold exp and log operators are a way to map between a manifold and vector space for computation

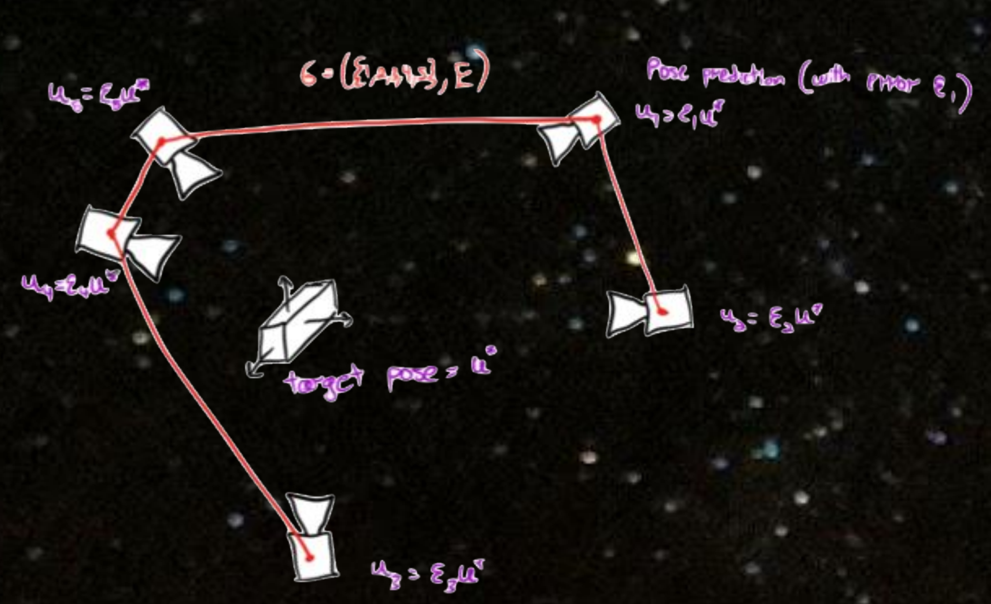


Illustration of camera-equipped satellites orbiting some uncooperative target.

Objective

Given:

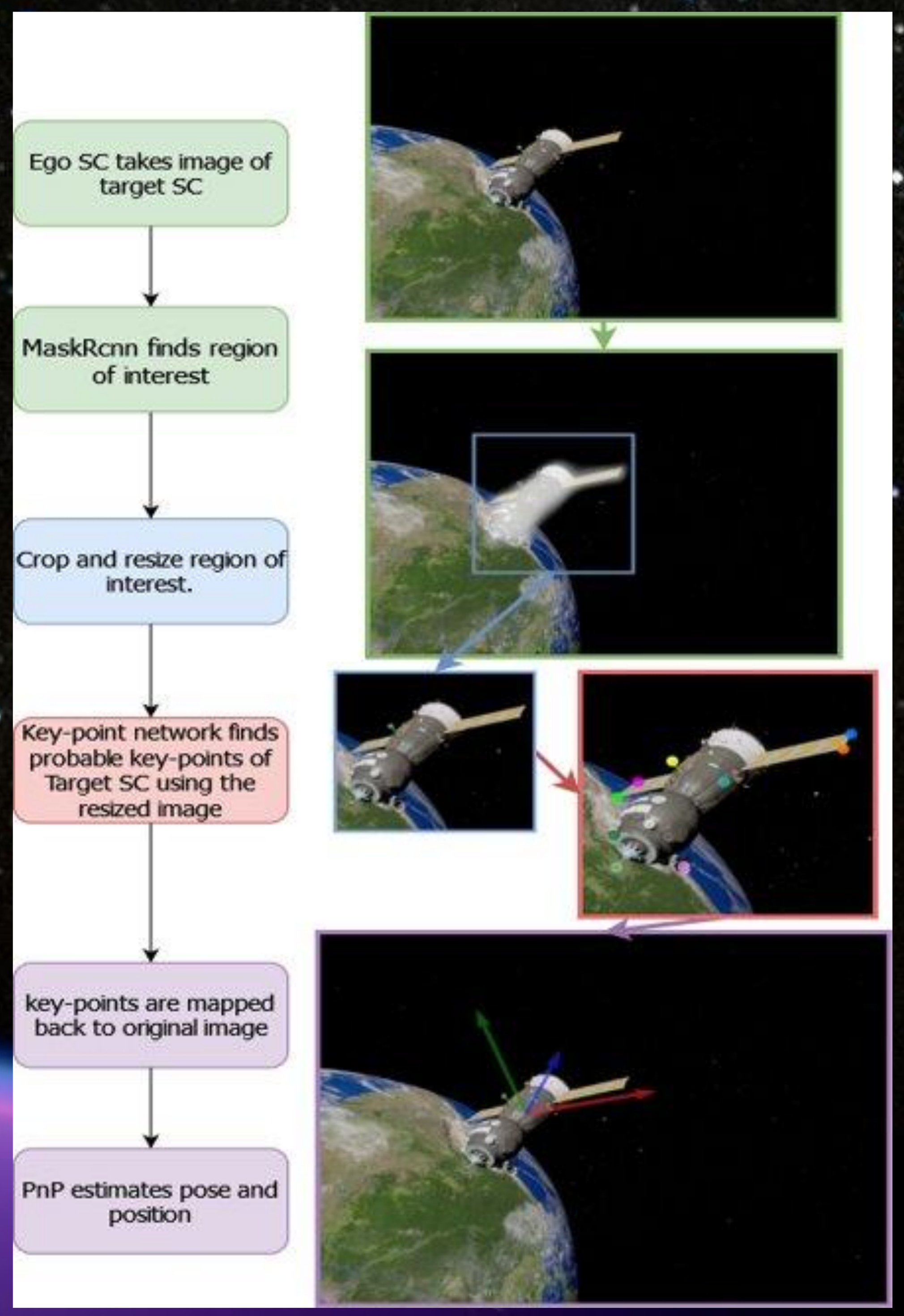
- Ability to synthesis any orbital environment
- Spinning uncooperative spacecraft (no IMU, gyroscope, accelerometer, etc. on spacecraft)

Goal:

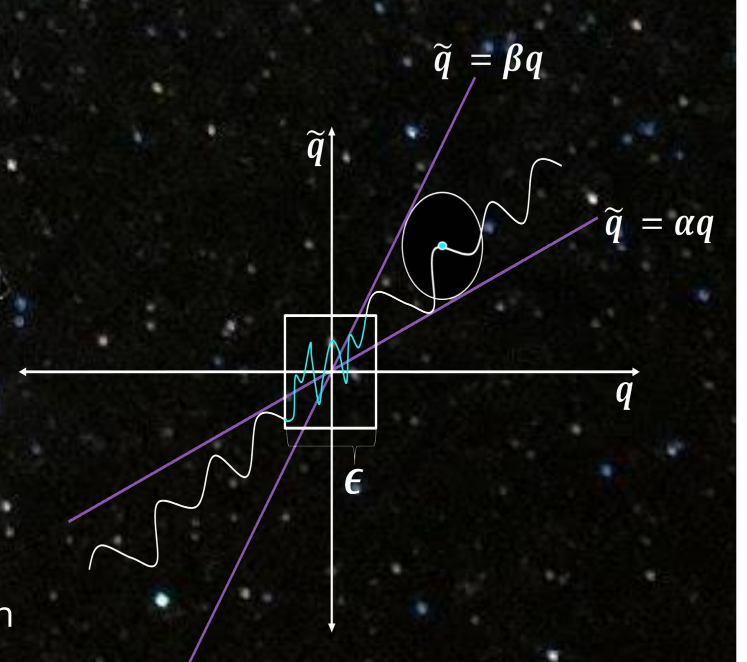
- Train neural network on synthesized data for (relative) pose estimation of some uncooperative space debris (target)
- Generate scenario of 6 camera-equipped satellites orbiting (spinning) target under some communication graph
- Use an intrinsic consensus algorithms on SO(3) for the sensor network to compute the (time-varying) "average" attitude of the target estimations in a distributed fashion

Motivation

- Taking the Euclidean average and projecting onto SO(3) will give different results with different embeddings (e.g., Unit quaternions, Rodrigues parameters, rotation matrices, etc.)
- RCM is always the same (up to the isometric mapping between the different embeddings)



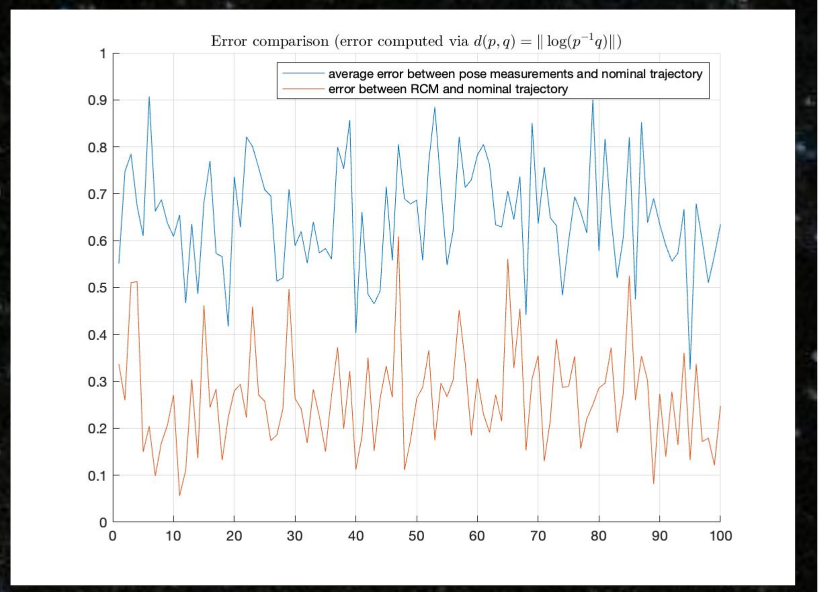
Orientation estimation by neural network on test case of target satellite

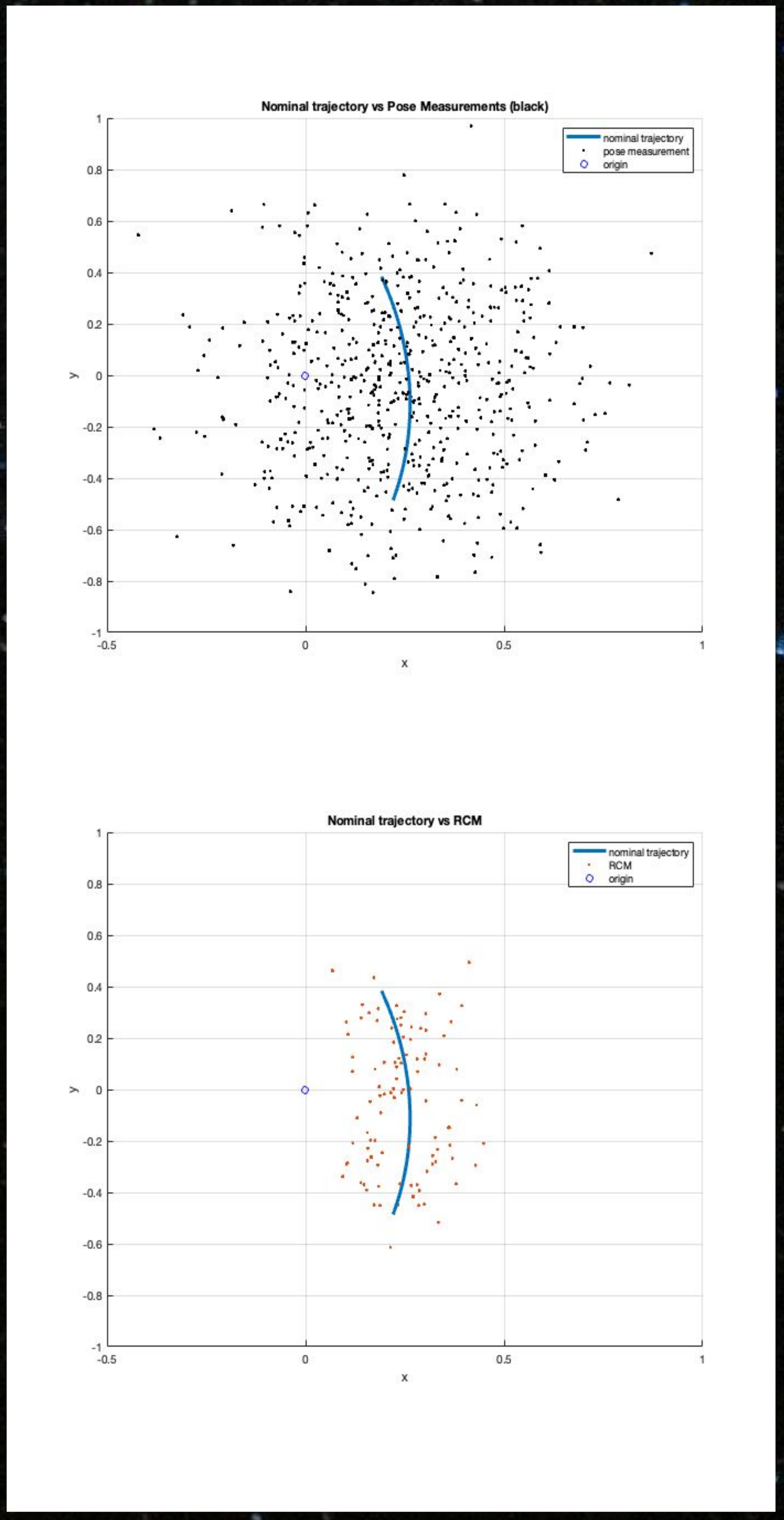


Error profile of neural network characterized as non-linear sector bounds.

Results

(top) The nominal trajectory plotted alongside the pose measurements (Rodrigues parameters). (bottom) The nominal trajectory plotted alongside the computed RCM.





Future Work, References, and Acknowledgments

- Applying consensus in a Dynamic setting where information from dynamics can be used to filter state estimates. This involves solving an optimization problem reducing estimation error over a trajectory constrained to attitude dynamics.
- Applications extending to rendezvous and docking with the unknown satellite.
- Comparision with conventional dynamic consensus algorithm like averaging consensus.

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