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Appearance-Aware Trajectory Optimisation for Autonomous On-Orbit Inspection

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Introduction

Modern space engineering increasingly focuses on designing long-lasting missions which depend on advanced on-orbit capabilities such as refuelling, servicing, and manufacturing. A critical aspect of these operations is visual on-orbit inspection for identifying and diagnosing problems in high-value satellites. Satellite materials like solar panels, multi-layer insulation, and structural components are difficult to inspect owing to their view-dependent (non-Lambertian) appearances. The dynamic and unattenuated illumination in orbit leads to direct specular reflections and deep shadowing, producing extremely high dynamic range scenes and saturated regions of imagery. These visual conditions can cause challenges for on-orbit inspection [1], potentially causing longer inspection missions and high data loads as more images need to be captured over time under better lighting conditions.

This work proposes an *appearance-aware* path-planning approach that models visual conditions in orbit, including time and view-dependent appearance, to plan efficient inspection trajectories as shown in **Fig 1**. We consider not only 3D geometry, but also view-dependent reflectance properties of materials and the position of time-dependent light sources such as the Sun. We propose appearance-aware cost functions for evaluating the optimality of camera poses under known lighting conditions. We integrate these time- and view-varying cost maps into a path-planning pipeline resulting in optimal trajectories for satellite inspection, minimising specular reflections. We provide the ability to weigh the two task objects as desired by operators. Early results from simulated satellite inspection operations show that our approach improves the quality of image capture when compared to an appearance-indifferent approach.

This extended abstract presents an overview of our method, and an illustrative example demonstrating its potential for use in on-orbit inspection.

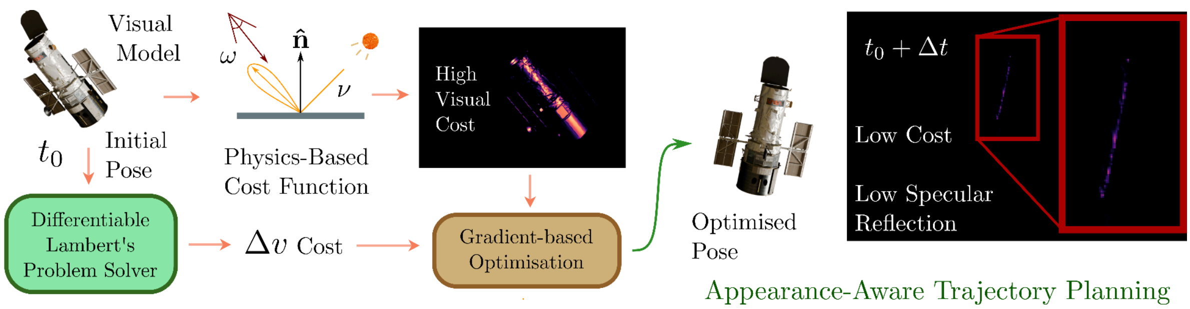

Fig 1. Our trajectory planning pipeline yields views which minimise specular reflections from the sun using a physics-based visual cost function. We leverage photorealistic simulation with time dependent lighting and a differentiable construction of Lambert's problem to optimise trajectories.

Approach

We consider the problem of visually inspecting a cooperative satellite using a chaser spacecraft. We formulate a task where the chaser, from a fixed starting state, must execute an impulsive manoeuvre to reach a future image capture point. The chaser must decide the final state and image capture time, trading off between both the fuel cost (Δv) and a visual cost as in **Fig. 1**. Our visual cost penalises specular reflections which provide poor signal on the condition of the underlying surface to be inspected, and they risk saturating camera sensors.

We assume there is a known visual model of the spacecraft (e.g., from CAD) and the spacecraft's orbital elements can be determined. We formulate the task as an optimisation problem, where the manoeuvre time and the initial and final positions are implicitly related to initial and final orbital velocities through the solution to Lambert's problem. To enable gradient-based optimisation of the trajectory, we propose a novel Lambert's problem solver that uses a differentiable root-solving routine, allowing efficient differentiation of the solution through the implicit function theorem. At each optimisation iteration, for a given satellite appearance model, orbital elements, chaser pose, and image capture time, we compute the satellite position through an orbital propagator and find the time-dependent sun vector and surface normals. We use the Lambert solver to compute a Δv which we assign as a fuel cost. We use a customisable pinhole camera model to project rays and a physically-based Phong reflection model [2] to assign costs to specular components of the solar reflections. Through JAX [3], a differentiable programming toolkit, we can calculate and optimise the cost with first-order gradient-based solvers to optimise a weighted sum of the fuel cost and visual cost.

As an illustrative example, we use Blender in-the-loop with our optimisation process as the source of the 3D visual model, providing depth and surface normals visible from a given inspection position, along with realistic rendering for simulation. An overview of our pipeline can be seen in **Fig. 1**.

Conclusion and Future work

By considering the visual appearance of a spacecraft and unique environmental lighting conditions present in orbit, this work paves the way for faster, higher fidelity, and more cost-efficient on-orbit inspection. In the future, we plan to extend this work by including modern data-driven representations such as Neural Radiance Fields, which provide high fidelity end-to-end differentiable visual models. We also plan to incorporate more complex visual costs and link visual inspection planning with real-time continuous control and tracking.

Acknowledgments

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