REALISTIC SMALL-BODY IMAGERY DATA GENERATION IN A CONTROLLED LAB ENVIRONMENT

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Abstract. *An in-lab imagery data sequence of a mock small-body, with the associated ground truth camera trajectory, is produced by utilizing an experimental spacecraft simulator, for the purpose of validating vision-based algorithms pertaining to small-body proximity operations. Realism of the image sequence is obtained by using appropriate lighting and camera optics, emulating in-space lighting conditions, while tracking camera trajectories which simulate orbital motion.*

Introduction. Precise relative navigation techniques, incorporating increased levels of autonomy, will be a key enabling element of future small-body orbiter missions.[1] Good navigation can inform safe and efficient path planning, control execution, and maneuvering. Validation using imagery and trajectory data is key in demonstrating the applicability, validity and reliability of novel autonomous navigation solutions for real-life small-body missions involving approach and proximity operations. Efforts to validate algorithms, such as Simultaneous Localization and Mapping (SLAM), for small-body exploration have been carried out in various previous works, using legacy mission data,[2] or simulated imagery.[3,4]

Several challenges typically arise when generating high-fidelity data for the purpose of validating vision-based navigation algorithms dedicated to near-small-body navigation on the ground. These are borne out of the difficulties in accurately emulating the in-space lighting conditions, simulating real camera effects and executing realistic relative motion predicated on the specific dynamics encountered in proximity of a small-body. Specifically, these challenges include a) illuminating the surface of the target small-body using a collimated-beam light source which emulates parallel Sun rays while limiting any other unrealistic diffuse lighting, b) emulating real-mission scales, in terms of relative distance to small-body and camera field-of-view angle, c) simulating spacecraft motion which incorporates real-mission forces, such as solar radiation pressure and non-spherical gravitational attraction, d) exploiting non-ideal camera images with realistic noise included, f) generating appropriate camera pose ground truth data for validation purposes, and e) mitigating ambient atmospheric light scattering off of the small-body during acquisition of images.

In this work, we tackle all but one of these challenges (the last) by generating realistic imagery using in-lab hardware. We use image and ground-truth data generated at the **A**utonomous **S**pacecraf**t** **R**obotic **O**perations in **S**pace (ASTROS) experimental facility,[5] located at the Dynamics and Control Systems Laboratory of the Georgia Institute of Technology.

Experimental Setup. The ASTROS facility houses an eponymous 5 degree-of-freedom spacecraft simulator test-bed, a 7 degree-of-freedom robotic manipulator system (RMS) consisting of a Schenck™ linear stage and a Universal Robots™ UR10e robotic arm, a 12-camera VICON™ motion capture system, and a control room.

Mechanically, the ASTROS platform is composed of two structures, called the upper and lower stages. The motion of these two stages is restricted or rendered free by exploiting two pressurized-air bearing systems, allowing for frictionless motion in up to 5 degrees of freedom, 3 of which are of rotation and 2 of translation. A linear air-bearing system between the lower stage and the floor levitates its lower stage off the near-perfectly flat floor, providing two degrees of planar translation plus one degree of rotation (2+1 configuration). Additionally, a hemispherical air-bearing allows for free rotation of the upper stage around two perpendicular horizontal axes. For the purposes of this experiment, the hemispherical joint is maintained fixed at a preset attitude, and hence the test-bed is in 2+1 configuration.

The platform is fitted with 12 cold-air gas thrusters which, when firing, generate forces and torques to allow it to actively maneuver in the test arena. The actuation of the thrusters is performed by dedicated power electronics in response to control computed on an embedded SpeedGoat™ computer. The computer compiles and executes a program derived from a prototyped Simulink model incorporating sensor measurement acquisition, control computation, actuator allocation and input-output communications with devices on the platform in real-time.

The test-bed also possesses an inertial measurement unit and a rate gyro, which when paired with an extended Kalman filter, allow it to estimate the position, attitude, linear velocity and angular velocity of the upper stage, used as feedback during position and attitude tracking.

The full experimental setup is illustrated in Figure 2.

Approach & Results. To capture images, we used a Teledyne FLIR™ Flea3 visible-spectrum global-shutter camera along with a MegaPixel 25-135 mm tele-objective lens. Set at around 100 mm focal length, the lens produces a field-of-view angle of about 5° to mimic the navigation camera of a typical asteroid surveying mission. The size of the mock asteroid and working distance were chosen accordingly to produce an apparent size of the mock asteroid in the image corresponding to 700-800 pixels in the horizontal direction. An on-board NVidia TX1 computer acquired sequences of images of the mock asteroid as the ASTROS platform maneuvered in the arena.

To emulate space-like lighting, typically characterized by collimated-light rays arriving from a source infinitely far away, a tight-beam stage lighting source was used. The light source, a Source 4™ Ellipsoidal with a 5° beam angle constrained by dedicated optics, illuminates the target mock asteroid throughout the experiment. Note that the light source is fixed inertially. This mimics the scenario in space where, for the short duration of the navigation segment, there is negligible angular change in sunlight direction, when viewed inertially. Although the challenge of light back-scattering still persists due to the presence of atmosphere in the facility, the tight-beam light source produces very crisp and harsh shadowing in the captured images. A sample of the image sequence captured in the ASTROS experiment can be viewed in Figure 3.

To emulate a true unforced orbital motion, idealized trajectories were generated and tracked in the ASTROS facility test arena. These trajectories were re-scaled via non-dimensionalization and redimensionalization to fit the physical limits of the arena and the safe allowable velocities, while achieving a reasonably long segment duration and speed-to-downrange-distance ratio which emulate the real mission scenario.

For simplicity, we fix the position of the asteroid in the test arena, and we rotate it at a constant angular velocity around a single body axis. To further simplify the planned maneuver in the ASTROS arena, we devise a planar orbital trajectory.

We restrict the motion of the test-bed to the 2+1 planar case, by fixing the rotation of the upper stage and freeing the lower stage to move along the inertial x-y directions, and rotate around the inertial z direction. We impose that the vertical component of the asteroid's inertial position correspond to the vertical component of the inertial position of the camera frame.

To achieve the level of precision required to simulate orbital motion, all of the parameters relevant to the experiment were estimated using accurate calibration schemes. Specifically, we carried out the accurate determination of the asteroid mounting boom length, the estimation of the RMS home position and attitude, the simultaneous calibration of the camera position and attitude relative to the upper stage and of the camera intrinsic parameters, using 2D-to-3D correspondences induced by taking images of a known 3D calibration target.

To manipulate the mock asteroid in the arena, the RMS was employed in open-loop control mode. Using the linear stage and robotic arm joint encoder values only, we achieve sub-millimeter end-effector inertial positioning error in the test arena.

Throughout the experiment, the motion capture system's UDP data stream was used to save the position and attitude of the ASTROS upper stage at 100Hz frequency. The frame number index of the data stream was subsequently used to synchronize and time-stamp all signal histories across the multiple devices, thus providing a single clock baseline for all the acquired data.

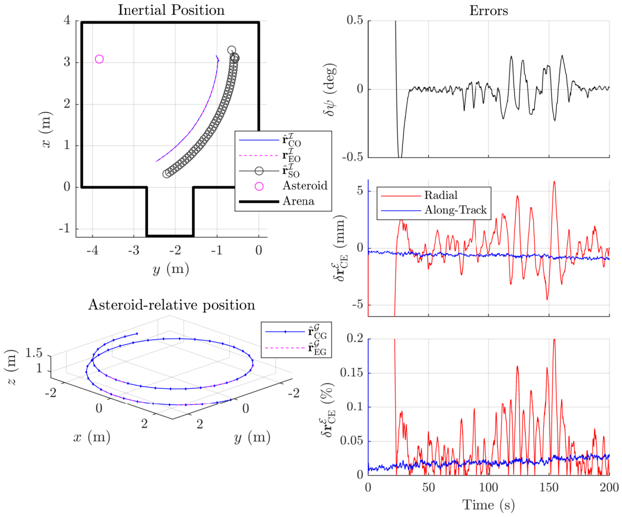

Figure 1. ASTROS lab experiment idealized trajectory and tracking errors.

Conclusion. An image sequence of a mock small-body, with sharp shadowing, dark background and high-contrast surface features, indicative of a collimated-beam lighting, has been produced along with the associated ground truth trajectory data. Position tracking of the idealized camera trajectory was performed with millimetric precision in lab scale, thus emulating realistic orbital motion in simulated orbit scale.

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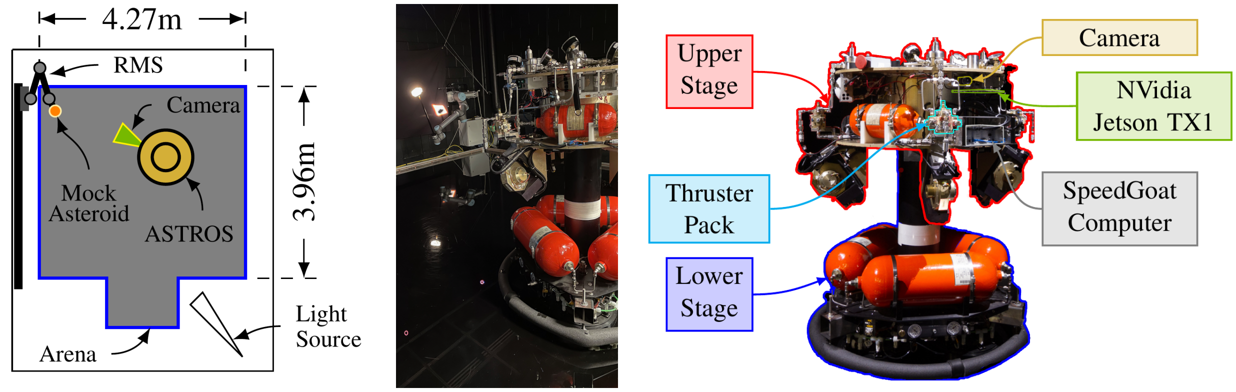
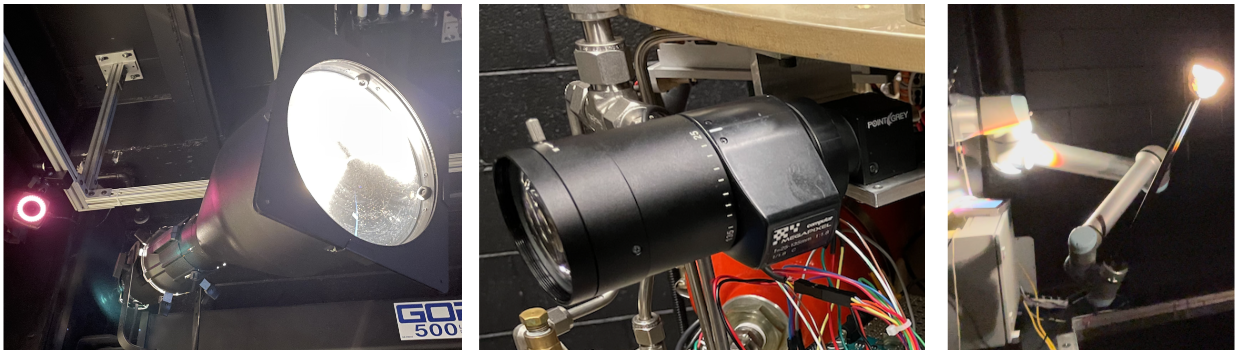


(a) Disposition of Devices in Arena *(b) ASTROS in Arena* *(c) Main Components of ASTROS Test Bed*



(d) Collimated-Beam Light Source and VICON Motion Capture System *(e) Small FOV camera optics* *(f) RMS and mock asteroid*

Figure 2. `AstroSLAM` experiment setup.

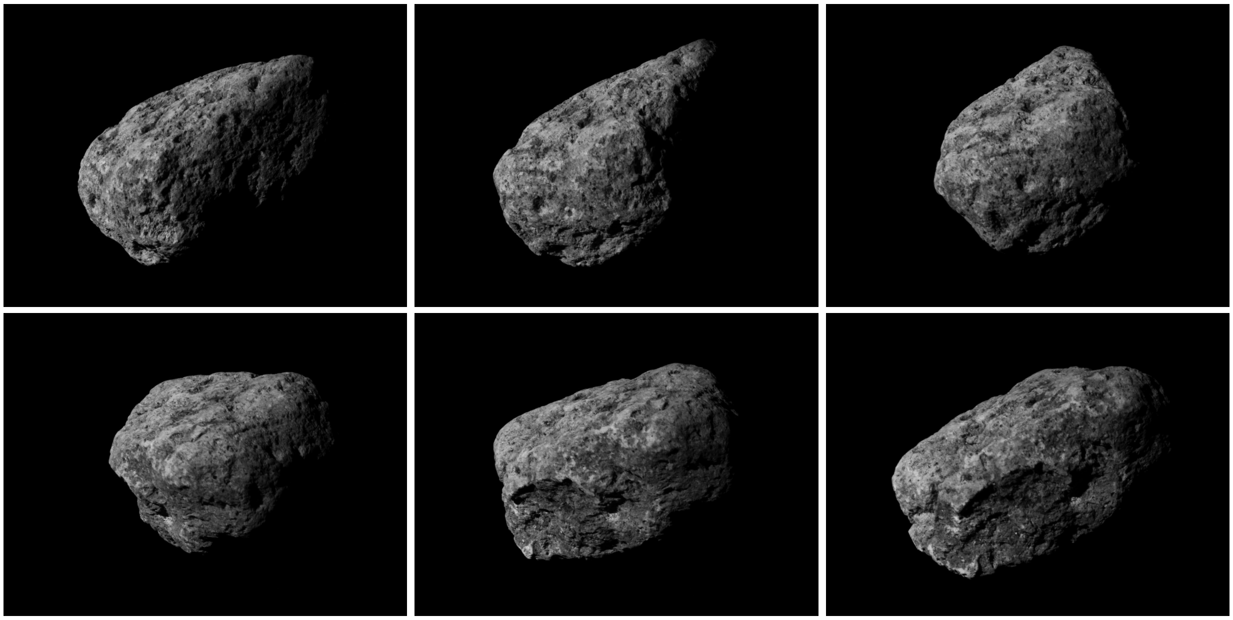


Figure 3. Captured images from the ASTROS experiment sequence.