Spotting Tango

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Project Description

We propose to simulate the motion of two spacecraft in low Earth orbit, where the chaser spacecraft is imaging the target spacecraft with a monocular camera. The image above is of the "Tango" spacecraft from the PRISMA mission by German Aerospace Center (DLR). The simulation's output will be the images from this monocular camera. The project will consist of three distinct goals:

Goals

1. Define a target spacecraft with high fidelity geometric and illumination properties
2. Define a 3D environment consisting of the Earth, the Sun, and the stars
3. Perform a physics-based orbit and attitude propagation of the target spacecraft and the camera

Technical Challenges

The relative motion between the two spacecraft and each of the illumination sources (Sun, Earth, Moon) is inherently complex which we will strive to model using first principle physics. The reflected light off of Tango is a function of the vehicle's orientation relative to the illumination sources and the observer, the vehicle's material properties, and the inter-spacecraft separation. Simulating realistic space-borne vision based navigation relies on accurately depicting each of these characteristics in high fidelity, and we feel that the technical challenges of this project stem from the realistic physical representation of the vehicle's motion in a dynamically changing illuminated scene.

Related Work

Great emphasis has been placed on the development of spacecraft capable of autonomous formation flying and rendezvous operations in recent years. Such spacecraft could be used in a missions to fulfill a wide variety of scientific missions such as solar coronagraphs, synthetic aperture radars, discovering exoplanets and enabling the development of future space civilizations. Historically, autonomous spacecraft docking is either performed using expensive, heavy, power-consumptive sensors such as LIDAR or aided through inter-spacecraft communication links. Use of such sensors or setting up inter-spacecraft communication links is ill-suited for smaller missions with budget, mass and power constraints or for applications such as debris removal. We seek to develop an autonomous docking solution which utilizes a single affordable, lightweight and power-friendly sensor. A monocular camera is a fitting candidate to meet the aforementioned criteria. With these motivating thoughts in mind, we seek to emulate autonomous spacecraft docking through the use of robotic mechanisms to validate our vision based navigation algorithms. The fundamental challenge which needs to be addressed when performing rendezvous operations in space is to position and orient the two vehicles relative to each other while minimizing the relative motion between them. Extending this functioning principle to an autonomous capacity requires that the chaser spacecraft is able to characterize the observed relative motion, and actuate corrective motion commands to safely approach the target vehicle.

Technical Details

Physics Simulation

We use first principle physics to simulate the dynamic motion of the vehicle. We model the gravitational attraction between two bodies using the fundamental orbital differential equation.

$$\frac{\mathrm{d}^2\vec{\mathbf{r}}}{\mathrm{d}t^2} + \mu\frac{\vec{\mathbf{r}}}{r^3} = 0$$

We numerically integrate this differential equation from a known set of initial conditions to propagate the translational evolution of the vehicle's center of mass expressed in the Earth Centered Inertial (ECI) coordinate system.

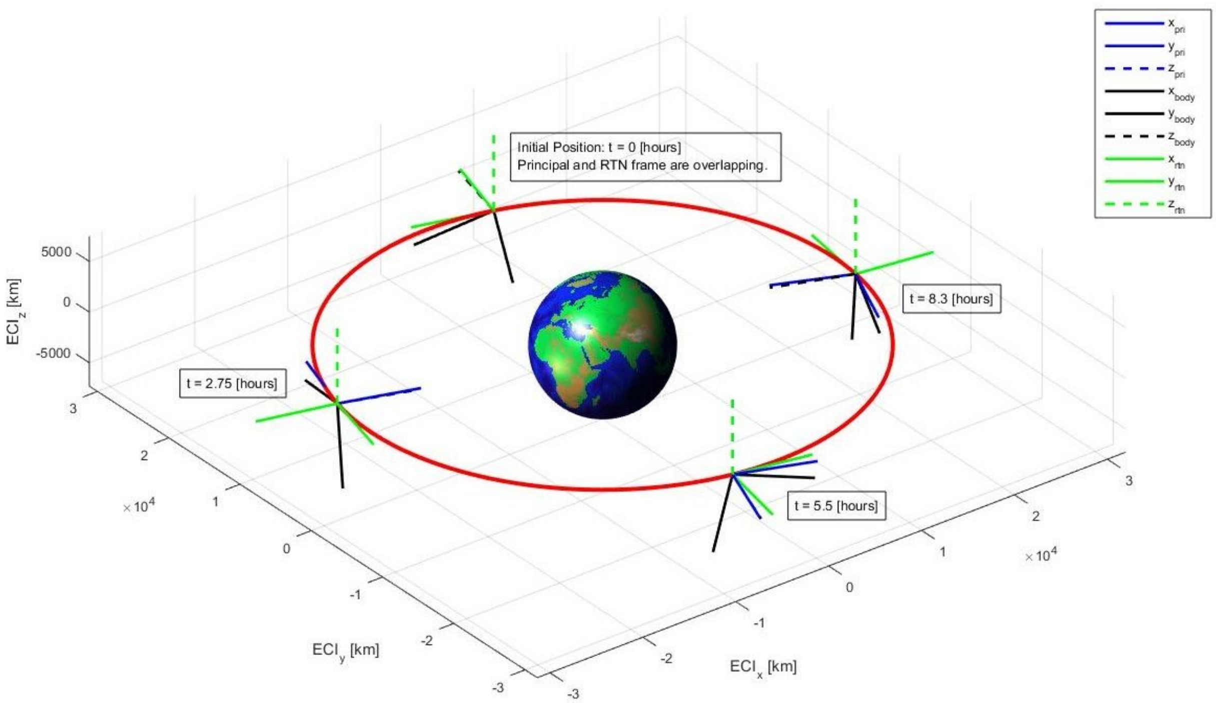
The vehicle's attitude is modeled using the Euler Equations, in which the initial angular momentum of the vehicle is conserved in the absence of torques.

$$0 = \frac{\mathrm{d}^{\mathrm{I}}\vec{\mathbf{L}}}{\mathrm{d}t} = \frac{\mathrm{d}^{\mathrm{R}}\vec{\mathbf{L}}}{\mathrm{d}t} + \vec{\boldsymbol{\omega}}_{\mathrm{R/I}} \times \vec{\mathbf{L}}$$

Again, numerical integration is employed to solve for time evolution of the angular velocity. Once the angular rates at each time step are known, we can use quaternion kinematics to propagate the evolution of the vehicle's attitude

$$\frac{dq}{dt} = \frac{1}{2} \begin{bmatrix} 0 & \omega_z & -\omega_y & \omega_x \\ -\omega_z & 0 & \omega_x & \omega_y \\ \omega_y & -\omega_x & 0 & \omega_z \\ -\omega_x & -\omega_y & -\omega_z & 0 \end{bmatrix} \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix}$$

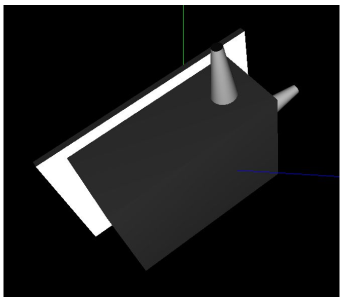
As we had previously mentioned, our intention is to perform this somewhat involved mathematical task in MATLAB to simplify our development efforts. We are happy to report (after much debugging), that we have successfully simulated the motion of the Tango spacecraft and are exporting the vehicle's spatial location in ECI coordinates along with its attitude relative to the ECI coordinate system. Here is a visualization of what the orbit and attitude evolution looks like:

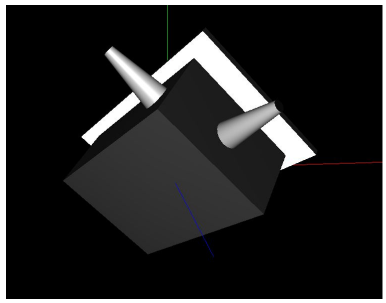


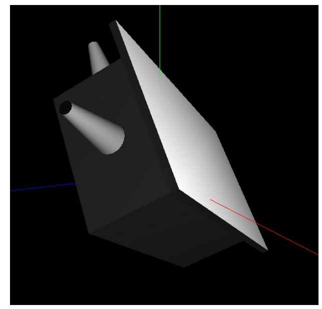
Moving forward our intention is to read the contents of this text file into OpenGL and translate and rotate the vehicle to emulate the simulated motion.

Spacecraft Model

We currently have implemented two different versions of the Tango spacecraft. The first version utilizes some of the intrinsic shape features (i.e. glutSolidCube, gluCylinder) and a collection of matrix operations (i.e. glTranslatef, glRotatef, glScaled) to build up the model of the vehicle. All in all, it actually looks pretty legit considering the real vehicle from a shape standpoint, however the lack of texture is a major discrepancy source when comparing the original (see cover page) to the simulated image. One question we would like to investigate more ourselves (and with the teaching staff) is how easy it is to apply textures to a solid model created using this approach (we welcome any advice)

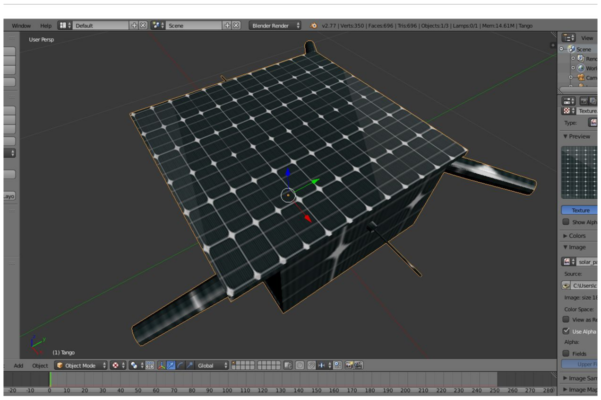


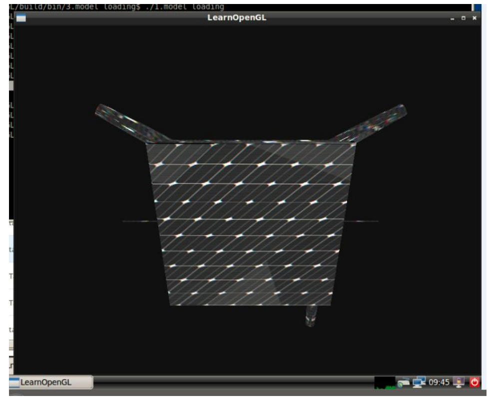




The second spacecraft model we pursued was inspired by utilizing the Assimp model loading library. This process began with the creation of the Tango spacecraft model in a computer aided design software (SolidWorks), exporting the model to an .stl file, importing the file into Blender, applying textures within blender, exporting the file to .obj format, and loading the model into our graphical window with the Assimp library. One unexpected hurdle that we are currently trying to resolve is the application of a texture (solar panels on the spacecraft) within Blender has the intended appearance, but upon loading and rendering with Assimp produces an altered result.

For the motion of the satellite itself, we employed the Hill-Clohessey-Wiltshire state transition matrix in MATLAB. This transition matrix gives the relative position of the target spacecraft in the RTN frame attached to the chaser spacecraft (location of the camera). This state transition matrix assumes a near circular orbit with no third body perturbations or effects of the Earth's oblateness. We then map this RTN position of the target to the model matrix in OpenGL and render the Tango spacecraft with its texture.





Environment

Stars

We have parsed the binary Hipparcos star catalog available to the public and now have a working database of each star's angular location within the celestial sphere, visual magnitude and B-V index (color of star). These three pieces of information in conjunction with the attitude of the vehicle will be used to render stars into a location on the screen which emulates the angular separation that would be observed in outer-space. Our intention is to illuminate a region of pixels with varying intensity using a 2D Gaussian point spread function (PSF) to simulate the "blurry roll-off" one would notice if they took an image of the starry night sky. Check out our awesome video of the synthetic star-field evolving according to the simulated attitude of the vehicle. Upon the actual implementation, we elected to use obj spherical files with a white texture wrapped around it to simulate each of the stars. We then encoded their angular location by translating the star to positions on the screen which matched the geometry coming from the coordinate transformation of each star's earth centered inertial (ECI) location to the camera frame.

Earth

For the model of the Earth, we loaded two spherical .OBJ files using the Assimp library. The spheres had the daytime and night-time texture applied to them, respectively. Both the texture files were obtained from the NASA visible Earth website. The idea was to have separate fragment shaders for the two spheres so that they can individually be colored in based on the direction of the light (the Sun). This had an effect of producing night lights when the camera was in eclipse. We also loaded a third sphere to create the atmosphere. This third sphere was made to be slightly blue in color and 10% larger than the two spheres representing the Earth. Its fragment shader imparted a 0.2 to its alpha channel to produce transparency. This had an effect of producing the glow in the atmosphere even when the camera was in eclipse. The Earth was placed at a fixed point in world space and rotated at a rate which matched the motion of the satellite. More precisely, we know that the Tango spacecraft was at an altitude of ~700 [km] in a direct orbit, this provides us the angular velocity of the Earth relative to the satellite.

Sun

We modeled the Sun as a simple light source in the scene. More importantly, we made sure the angular velocity of the Sun to represented the angular velocity of an orbit in low Earth orbit.

Final Product

We were able to tie together many principles that we learned from the class into this project to create a pretty stunning result. Vertex and fragment shaders were employed along with the Phong shading model to emulate the diffuse, specular and ambient light reflecting off the solar illuminated Earth. Since the observation of the Tango spacecraft is from the perspective of the chief spacecraft, the relative position of the Sun is changing throughout the vehicle's orbit. By changing reference frames, we were able to describe the relative position of the "inertially fixed" Sun from the perspective of the chief spacecraft, which was used to emulate the beautiful insolation/eclipse transitions throughout our vehicles orbit around the planet. Two different textures were used to visualize the appearance of the Earth when in eclipse and sunlight. Throughout much of this project we employed and demonstrated our comprehension of the OpenGL matrix stack to achieve many operations such as translating the Tango spacecraft, moving the Earth into the proper position, rotating the Earth about a body-fixed axis, rotating the Tango spacecraft vehicle about its center of mass. We learned a tremendous amount about geometric modeling, texture mapping, handling the .obj file format to create the Tango spacecraft, Earth, and stars. We additionally were inspired by lectures on physics and its importance of visualizing physical mechanisms through graphics. In this light we feel that we have displayed one our strongest project characteristics which is an embodiment of first principle physics to describe a physically meaningful visualization of a scene. We solved a pair of differential equations and propagated a set of initial conditions for the vehicle's location and orientation to produce a stunning depiction of how the Tango spacecraft is predicted to tumble in space. All in all we feel that our efforts on this project synergizes many facets of this class and manifested to produce the following video presentation: https://vimeo.com/178529266