PRE-ARRIVAL DEPLOYMENT ANALYSIS AND TRAJECTORY RECONSTRUCTION OF HAYABUSA2 ROVERS. S. Van wal[1], Y. Tsuda[2], K. Yoshikawa[2], A. Miura[2], S. Tanaka[2], and D. Scheeres[1]. [1]Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder (431 UCB, Boulder, Colorado 80309) for first author, [2]Japan Aerospace Exploration Agency (Sagamihara, Japan 252-5210).

Introduction: The Hayabusa2 asteroid explorer was launched by the Japan Aerospace Exploration Agency (JAXA) in December 2014 and plans to return samples from the near-Earth asteroid Ryugu. One sample will be taken from a crater that is artificially created using an explosive impactor. Hayabusa2 will also deploy three Japanese "MINERVA-II" rovers and one European "MASCOT" lander [1, 2, 3]. The rover deployment must be designed in compliance with various mission requirements, most notably the exclusion of the neighborhood around the candidate Hayabusa2 sample sites. Prediction of the rover descent trajectories may also assist with the scheduling of tracking and communications. Uncertainties about the asteroid system in general, and its surface properties in particular, make it challenging to accurately predict the rover motion. We have performed a pre-arrival deployment analysis in preparation for Hayabusa2's arrival at Ryugu in June/July 2018, and discuss our planned approach to estimate Ryugu's surface properties from the observed/reconstructed lander motion.

Asteroid Ryugu: Asteroid Ryugu is a carbonaceous near-Earth asteroid of approximately 800 m diameter. It orbits between Earth and Mars in a heliocentric orbit with a=1.2 AU and e=0.19. Ryugu's rotation period was obtained from lightcurves as P=7.631 hr, though the orientation of the rotation axis is only poorly estimated. Lacking radar observations, the best shape model of Ryugu was constructed from lightcurves as well, but is of severly limited resolution [4, 5]. Most properties of the Ryugu system will not be known to appreciable precision until arrival.

To enable extensive mission rehearsal, JAXA has therefore developed a *training model* for Ryugu. This high-resolution model was constructed by augmenting the low-resolution shape model with realistic surface details, such as craters, boulders, and hills. These terrain statistics are partially based on Hayabusa1 observations of asteroid Itokawa [6, 7].

The MINERVA-II Rovers: Hayabusa2 carries three small rovers, MINERVA-II-1A, -1B, and -2, developed by a consortium of Japanese universities. They have massed of approximately 1.2, 1.1, and 0.9 kg, carry a few small instruments, and have momentum exchange mechanisms that will allow them to demonstrate controlled mobility on Ryugu's surface [3]. The rovers are released from Hayabusa2 with a spring mechanism at an altitude of approximately 55 m, perpendicular to the Earth-Ryugu line. The asteroid-relative latitude of release is fixed by the day of release. The longitude of release is free, though the selected deployment scenario must comply with any mission constraints. The most important of these is the exclusion of the neighborhood around the targeted Hayabusa2 sample site. Rovers must avoid this neighborhood in order to avoid interfering with the autonomous Hayabusa2 descent guidance, which uses the reflection of deployable target markers as fixed landmarks with which to navigate down to Ryugu's surface. The presence of rovers near the sample site may generate secondary reflections that may upset the descent guidance.

Deployment Analysis: Although it is not possible to perform an accurate deployment analysis without models of the "real" Ryugu, we can perform a pre-arrival deployment analysis using the training model. This allows for verification of simulation software, identification of challenges/opportunities in the release sequence, and planning of the deployment analysis to be carried out following arrival.

We simulate rover motion using a constant-density polyhedron to model Ryugu's gravity, a signed distance field to model its shape, and an impulsive contact model that includes normal and Coulomb friction forces to evaluate the low-velocity rover-asteroid collisions. The latter is parameterized with a coefficient of restitution, e, and a coefficient of friction, f. For a detailed description of these models, the reader is referred to [8, 9]. Test simulations to the Ryugu reference sphere with equivalent volume as the training model were used to quantify the effects of variations in the restitution and friction coefficients. More importantly, these simulations indicated that the rover release velocity is particularly high, resulting in high tangential velocities at first impact, and large dispersions across Ryugu's surface. The extent of these dispersions makes it challenging, if not impossible, to reliably guarantee exclusion of any sample site neighborhood. To alleviate this concern, we include a horizontal pre-release maneuver (PRM) to be executed by Hayabusa2 just prior to rover release, such that the rover's tangential velocity at first impact is minimized. This PRM was found to successfully limit the rover dispersion in simulation to the Ryugu reference sphere.

We then applied this to perform simulations of deployment to the Ryugu training model. As Hayabusa2 maintains a fixed position along the Earth-Ryugu line, release is possible at any longitude above Ryugu's surface. We therefore simulate deployment at various latitudes, which effectively corresponds to deployment above various types of terrain. Each collision is evaluated using a random coefficient of restitution e = U(0.1, 0.6) and a fixed coefficient of restitution f = 0.6. We find a similar mean settling time of t~1.25 hr in all scenarios, though the standard deviation displays some variation (up to 50%). Larger differences (up to 200%) are found in the size of the surface dispersion area. We find that deployment to flat surface regions results in the largest surface dispersion, while deployment to a crater or basin results in the smallest surface dispersions. The "crater" deployments also result in the shortest settling times. This suggests that the targeting of a large crater is an easy way of minimizing the rover dispersion and avoiding a sample site exclusion zone. We show a sample deployment to the Ryugu training model in Fig. 1 below.

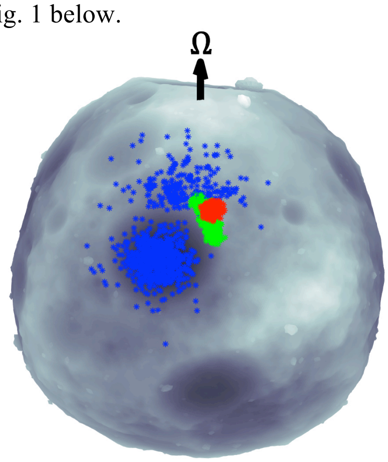

Fig. 1: Sample deployment to the training model.

Trajectory Reconstruction: The chaotic nature of the impact of a non-spherical object makes it challenging to provide predictions of ballistic deployment in which rovers bounce several times on the asteroid surface. This challenge is compounded by our limited knowledge of the dissipative properties of the surface. Conversely, a reconstruction of these bouncing trajectories allows for an estimation of surface properties.

Following the MINERVA-II rover deployment, we will reconstruct the descent trajectory and estimate the coefficients of restitution and friction. The first step in this will be an estimation of the rover release velocities. Given that this velocity determines the location of first impact, an estimation of the actual release velocity provides a strong constraint on the rover descent. The rover release applies an impulse to the Hayabusa2 mothership. Since the rovers are released perpendicular to the Earth-Ryugu line, this impulse is poorly observable from mothership range or range-rate measurements. However, the release impulse also applies a torque. Since Hayabusa2 autonomously maintains a fixed attitude, the applied impulse can be estimated from the Hayabusa2 attitude and the response of its reaction wheels. Combined with estimates of the Hayabusa2 position and velocity, this allows for accurate prediction of the first impact location.

Hayabusa2 carries a variety of optical navigation cameras that will attempt to track the MINERVA-II rovers as they descend to Ryugu's surface. Due to limitations of the camera field-of-view and geometry, this tracking is not guaranteed possible. Extensive simulation of the selected deployment scenario prior to release will provide predictions of the post-release rover motion that may improve the chances of successfully capturing the rover in the camera images. Such images would provide additional data that can be used to reconstruct the rover descent trajectory. If multiple images are available, the rover angular velocity may also be estimated from changes in the rover attitude.

Although there is no guarantee about the availability of on-board rover data, Hayabusa2 will continuously attempt to communicate with the rover as it descends to Ryugu's surface. The activity of this communication link will thus provide a line-of-sight visibility check. In combination with mothership position and attitude, this provides further constraint on the rover position at a given time. Once the rover settling position has been determined, we can perform extensive simulation to generate settling dispersions corresponding to the estimated release velocity, and some combination of e and f. We will examine any systematic behavior in the simulated collisions, and test a multitude of (e,f) sets in order to determine a maximum likelihood estimate of the values that result in the observed settling location. In turn, these coefficient values may provide information on the (sub-)structure of Ryugu's surface. They are also expected to improve the prediction accuracy of subsequent lander/rover deployments, and can be used in the design and operational planning of future small-body surface exploration missions.

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