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Lidar-Based Autonomous Rendezvous in Mars Orbit

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Abstract

This paper presents the results of an autonomous rendezvous simulation in Mars orbit. The analysis is conducted in the context of a terminal rendezvous sequence of a Mars Sample Return mission. Initial conditions are such that the chaser spacecraft is closing on a sample capsule target orbiting 5-km ahead at a higher altitude. The rendezvous algorithms used are discussed in the text. This includes a filter based on lidar data for relative navigation and a targeting scheme to compute the guidance maneuvers. An Extended Kalman Filter is used to process the lidar observations and estimate the orbit of the target. A description of the lidar measurement model is included. The guidance algorithm was developed using a Lambert targeting scheme. The prediction of both satellites' positions during the transfer is based on two-body dynamics.

True spacecraft motion is simulated via AGI's Satellite Tool Kit software. The selected orbit propagator from STK employs numerical integration to provide the most accurate representation of the truth. Based on the current position of both spacecrafts, lidar data is generated and fed back to the rendezvous software. The data is then used to estimate the target's position and to analyze the satellites' relative positions. Results show that both the filter and the Lambert scheme are successful in achieving rendezvous.

1 Introduction

Many countries have identified Mars as the next frontier in human space exploration. The success of such an endeavor is characterized by the completion of several innovative projects in all fields of science, from biology to engineering. One of these projects is to conduct a Mars Sample Return (MSR) mission. It is crutial to master the key technologies that have been identified as a necessity to the return of scientific material or crew on Earth. Among these is an autonomous rendezvous technique between the return ship and the orbiting sample capsule.

In its effort to participate in the exploration of Mars, the Canadian Space Agency (CSA) is currently developing a Guidance, Navigation and Control (GN&C) system for a rendezvous in Mars orbit. This study intends to provide the technical basis of a lidar-based GN&C system and to present the preliminary results obtained from simulation.

1.1 Terminal Rendezvous Approach Sequence

Although bringing back a sample from Mars has never been acomplished, serious thought has been given to the problem already. Studies have demonstrated that direct return to Earth from the Martian surface is very inefficient and nearly impossible. A rendezvous in orbit is therefore necessary to capture the sample capsule after its launch from the Martian surface. In addition, this allows different samples from different sites to be brought back to Earth using a single rendezvous spacecraft.

The rendezvous sequence offers many technical challenges that need to be addressed. First,

due to the limited guidance capabilities of a Mars ascent vehicle, the exact orbit of the sample capsule will probably not be known precisely. Although the capsule would likely be equipped with radio beacons, this will be insufficient to identify the orbit with the precision required for capture. In addition, while the initial tracking and guidance can be operated under ground command, the terminal rendezvous and capture phase needs to be autonomous. Roundtrip light time from Earth to Mars can be as long as 43 minutes. Moreover, other communication issues - such as the spacecraft being in Earth's shadow at a critical moment - make Earth-based navigation unfeasible. Consequently, the relative navigation must rely on onboard calculations.

The terminal rendezvous navigation will thus rely on two things: software and instruments. The prime instrument used for the relative navigation in this study is a Light Detection and Ranging, or LiDAR. Highly accurate, today's lidars can detect a target up to 5-km distant with a cm-level accuracy in range and to about 250 micro-radians in angles. As such, most space agencies considering Mars activities (NASA, CNES, ESA) have already identified Lidar as the prefered instrument for autonomous rendezvous [1, 2].

In the past years, NASA and CNES have joined their efforts to conduct studies on possible rendezvous scenarios. See for example Kachmar *et al.* [3]. Even though planned MSR missions were postponed due to budget restrictions in both of these countries, the subject still has a high priority and is of significant interest. More recently, ESA recognized the potential of lidar and is currently evaluating navigation concepts for lidar-based rendezvous through its Aurora program [2].

The scenario chosen for the simulation presented in this paper follows the work of Kachmar, D'Souza and Brand [3] of the Draper lab, in collaboration with JPL. They describe a co-elliptic approach strategy, for which the chaser satellite moves toward the target from behind, on an orbit of lower altitude. Although several scenarios are possible [4, 3], they identify several reasons in favor of the co-elliptic approach. As such, an analogous trajectory design was selected as the baseline of this study. The terminal rendezvous sequence is shown in Figure 1 for reference. It should be pointed out that since current lidar capabilities are limited to a 5-km maximum range, it is assumed that some initial orbit determination and targeting was performed using other instruments, such as a Radio Detection Finder (RDF). As a consequence, the simulation starts when the initial position is roughly known to be 0.2-km below and 5-km behind the target. The satellites are flying at an altitude of 300 km on near circular orbits.

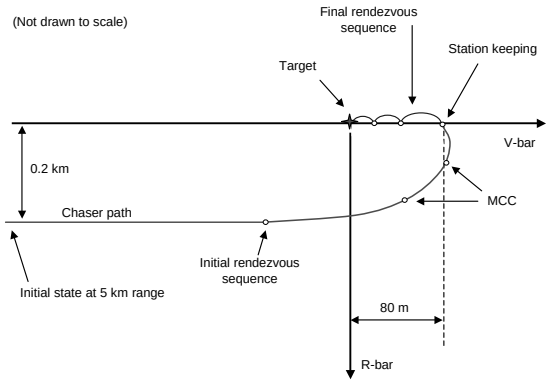

Figure 1: Approach Scenario

2 Guidance, Navigation & Control

The terminal rendezvous system is composed of three subsystems, the guidance, navigation, and flight control (GN&C) subsystems. The guidance algorithm computes the maneuvers required from the different steps of the scenario up to the final capture of the orbiting sample (the target). The navigation subsystem handles the estimation process of the relative orbit between the return vehicle (the chaser) and the target. The navigation relies on range and angle measurements from the lidar instrument. Finally, the flight control system directs thruster burns, based on inputs from the guidance subsystem. Since this part relies heavilly on hardware and attitude control, the focus for this study is on the first two subsystems.

2.1 LiDAR Measurement Model

The measurement model selected for this study consists of the absolute range and two directions cosines, aligned in RST frame of the imaging spacecraft. The direction cosines were chosen

due to the fact that unit vectors are better handled mathematically than angles. Quadrant sign problems arise when taking the trigonometric functions of the angles. In the event that the hardware is designed to send a different setup, the navigation algorithm can always be modified accordingly. A few lines of code can be added to transform the data from one reference frame to another, or to convert angles to direction cosines, for example.

The RST reference frame in which the lidar measurements are defined is as follows: $\hat{R}$ points in the direction of the position vector, $\hat{T}$ is perpendicular to the position and velocity vectors and $\hat{S}$ completes the orthogonal set and points *along* the velocity vector. The measurement model is:

$$\begin{aligned} \rho &= \|\mathbf{r}_{tgt} - \mathbf{r}_{chaser}\|; \\ l &= \mathbf{u} \cdot \hat{\mathbf{T}}; \\ m &= \mathbf{u} \cdot \hat{\mathbf{S}}; \\ n &= \mathbf{u} \cdot \hat{\mathbf{R}}. \end{aligned} \tag{1}$$

where $\mathbf{u}$ is the unit vector pointing along the relative range vector expressed in the J2000 Mars inertial frame. The *RST* vectors are also expressed in the inertial frame. Note that using all four is redundant as this model represents a three- dimentional vector. Therefore, one of the direction cosines was left out.

To process the above measurements and estimate the trajectory, their partial derivatives with respect to the state vector X_i is required. The partials with respect to the target position (X_i; $i = 1 : 3$) are:

$$\begin{aligned} \frac{\partial \rho}{\partial X_i} &= \frac{\rho_i}{\rho}; \\ \frac{\partial l}{\partial X_i} &= \frac{1}{\rho}[\hat{T}_i - l\mathbf{u_i}]; \\ \frac{\partial m}{\partial X_i} &= \frac{1}{\rho}[\hat{S}_i - m\mathbf{u_i}]; \end{aligned} \tag{2}$$

2.2 Kalman Filtering

The navigation algorithm employs a sequential estimation process to determine the target state in the Mars inertial frame. This method is prefered to traditional least-square methods as it is more convenient for real-time navigation. The rendezvous algorithm sequence indeed calls for a continous update of the state information with each new observation, since the maneuvers' execution time is solution-dependent. Also known as Kalman filters, sequential processing methods correspond essentially to a single iteration of the least square method. Furthermore, as the state update is needed at each measurement time, an Extended Kalman Filter (EKF) is chosen. The EKF makes use of the latest state estimate to propagate the state vector.

The filter assumes that the chaser's state is known from another source, such as the orbiter's main navigation subsystem. Essentially, the estimate of the target's position and velocity is achieved by processing the lidar data and comparing it with the measurement model. As stated in the previous sections, the observation model is evaluated based on the predicted/estimated spacecraft positions, where a force model representative of the dynamics of the Martian environment invovled is used.

The orbit propagator used here is limited to the J2-term perturbation for practical reasons. Further studies shall demonstrate to which point this should be extended. Plans to analyze relative motion directly using the linearized model known as Hill's equations, or better, a more complete model such as described in Ocampo *et al.* [5] is curently under investigation. The state vector consists of the 6 inertial position and velocity components of the target. Plans to include measurement biases and unmodeled acceleration are also under way.

2.3 Rendezvous Targeting

The targeting sequence has been divided in three steps for the purpose of this simulation: the initial rendezvous, a station keeping stage and the final rendezvous. The initial and final rendezvous are both conducted using the same logic and are composed of a first targeting maneuver, two mid-course corrections, and a stopping maneuver (Figure 1).

As described in the introduction, the chaser satellite is slowly approaching the target from behind while refining its relative position estimate. The first rendezvous sequence is initiated when the relative angle between the chaser path and the target reaches 78° [3]. At this point, a Lambert targeting algorithm is applied to compute the maneuvers required to place the chaser at a leading 80-m distance from the target. The maneuver is applied and the navigation system continues to gather data from the lidar and estimates the relative position during the transfer.

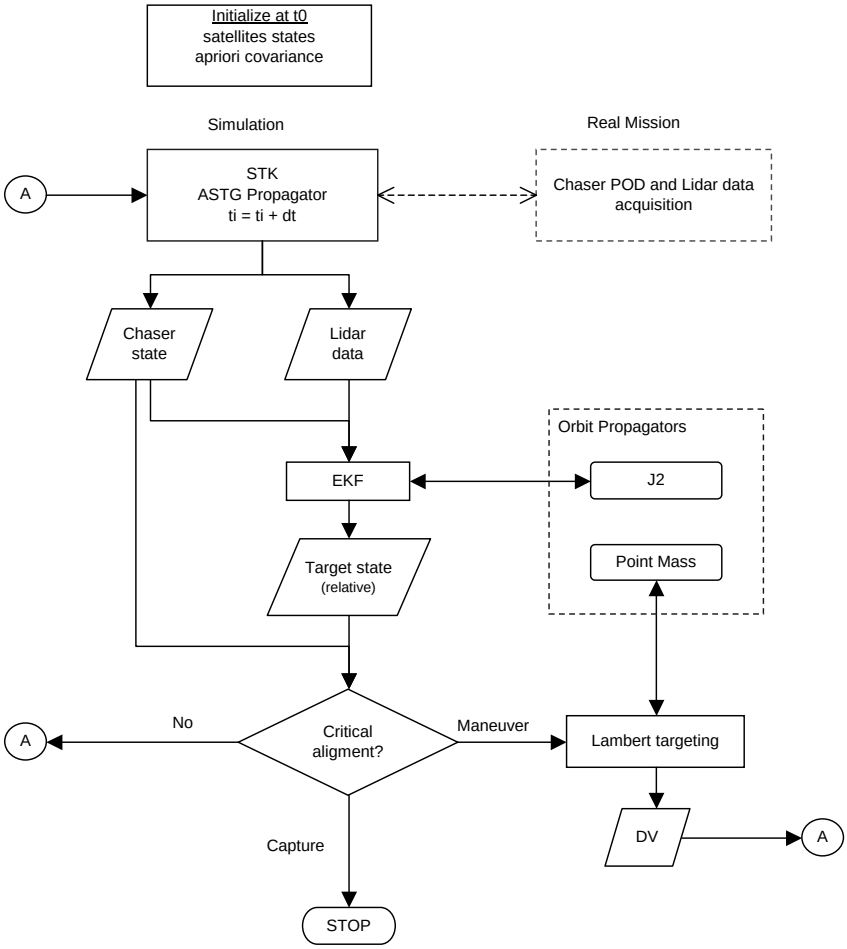

Figure 2: Rendezvous Algorithm Flow Chart

Two mid-course correction maneuvers are computed to account for propagation errors, partly because the Lambert algorithm assumes two-body motion to propagate the satellites. After reaching the 80-m baseline, a 25-minute station keeping phase is initiated to evaluate the situation and assess if any correction are required. The final rendezvous sequence follows, using an approach similar to the initial sequence.

An important point to discuss is the time of transfer between two maneuvers. This variable is currently fixed in the code at pre-determined values, based on optimal fuel usage. As too many unknowns exist in this situation, it is difficult to develop a code general enough to handle all possible scenarios. This point will be assess in the future. For now, the initial and the final sequences were fixed at 25 minutes and 20 minutes, respectively. The sequence as a whole has to be autonomous, although the station-keeping phase would most likely serves for ground control assessment. Autonomy is required between maneuvers since communication time from Earth to Mars is too long, as mentioned in the introduction.

3 Rendezvous Simulation

The algorithms described above were coded in Matlab and used together to simulate the rendezvous. The layout of the main routines involved is depicted in Figure 2.

The mission scenario was built up with AGI's Satellite Tool Kit software to simulate the truth environement. STK is used to provide the chaser satellite's state and to simulate the lidar data.

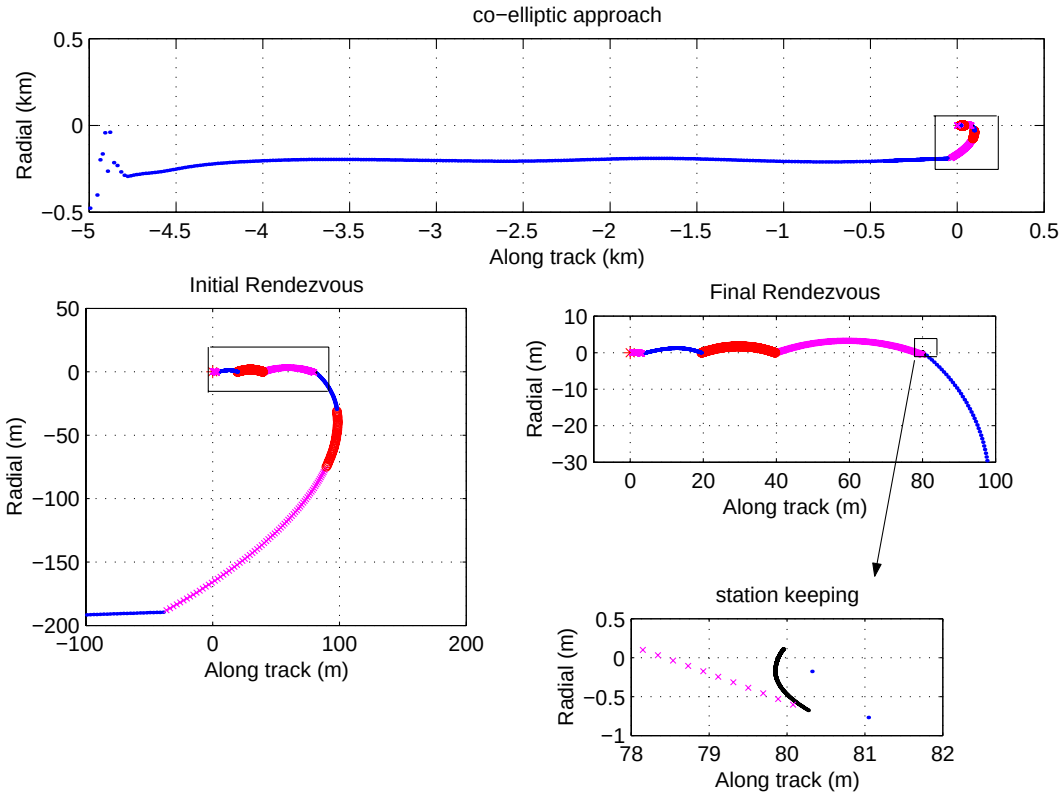

Figure 3: Trajectory Estimate

The chaser and the target vehicles are created using the setup described in the introduction as initial conditions. The lidar measurements are computed as the satellites fly and are fed back to the simulator together with the chaser's ephemeris. The chaser's flight computer (here matlab) uses the information for relative navigation and guidance. The interface between the GN&C system and STK is ensured via the STK/Connect module. It should be pointed out that STK/Astrogator module was used to ensure the proper numerical integration of the satellites in a martian environnement. Astrogator was also useful when adding burns to the scenario.

3.1 Results

Both the Kalman filter and the guidance scheme show promising results. Figure 3 shows the whole trajectory as estimated by the filter. The trajectory is represented in the moving reference frame of the target. The x-axis is along the the velocity vector (v-bar) and the y-axis along the radial position (anti r-bar). Also shown are close-ups of the different stages, clearly showing the maneuvers. It took perhaps 250 meters in relative trajectory for the filter to converge to a solution and approximatly a kilometer to get an accurate estimate. The smallest image shows where the station-keeping phase took place, represented by the dark continuous line. The small drift is caused by computer round-off errors and mainly the fact that two-body motion is assumed in the Lambert guidance algorithm.

Both the Lambert model and the Kalman filter prove to be sufficient enough to navigate the chaser within respectable limits. For example, the station-keeping phase takes 25 minutes, occasioning a drift of less than 1 meter.

The post-processing residuals of the lidar measurements are shown in Figure 4 and offer hints on how the filter behaves. The first plot corresponds to the range data; the other two plots correspond to the cross-track and in-track direction cosines. Measurement residuals rep-

resent the difference between the observed and the computed observations. In this study case, the observed data is built using the propagated ephemeris from STK, and the computed data is based on the estimated states of the two spacecrafts. As expected from such a system, the filter takes a very short time to converge to a solution during the approach (all lines converge to zero). Maneuvers are also visible towards the end of the simulation. The first maneuver is well recovered as the residuals reach the zero line for all three measurements. However, the model seems to have a hard time during the final rendezvous when the spacecrafts are very close to each other. It is suspected that computer round-off errors are the source of this problem since the two spacecraft states are almost identical.

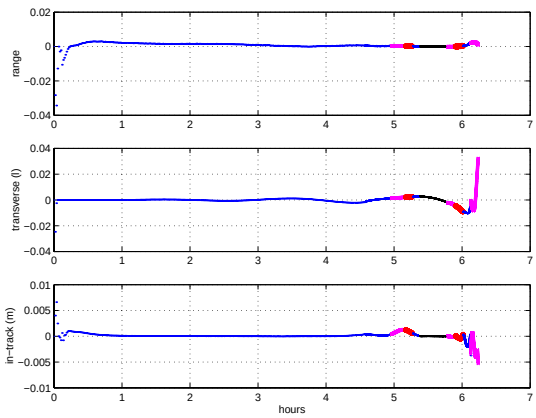

Figure 4: Measurements Residuals

4 Conclusions & Future Work

The work presented in this paper illustrates a guidance and navigation algorithm sequence developed for an on-orbit rendezvous around Mars. A navigation Kalman filter was built based on lidar observations to estimate the position and velocity of a target satellite. A simple J2 orbit propagator was used as it is hoped to be sufficient for relative navigation. The truth model simulated via the Satellite Tool Kit software also used a J2 propagator to demonstrate the filter's functionality. Future plans are to use a more complex force model to assess the filter's behavior. Different orbit propagator concepts may also be developed if necessary. The use of Hill's equation for relative motion will be investigated, even though the theory restricts the orbits to be near circular.

The rendezvous maneuver computation model was developed using Lambert targeting theory. The transfer times between two maneuvers were fixed prior to execution. Alternatives to this restriction will be explored in the future. Other algorithms might also be necessary, such as a station keeping scheduler to maintain a formation prior to the final capture.

With the current configuration, the Kalman filter and the Lambert scheme were sucessfully used together in a simulation of a rendezvous sequence considered for a Mars Sample Return mission.

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