MER Entry, Descent, and Landing Reconstruction Using an Unscented Kalman Filter

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Extended Abstract

The entry, descent, and landing (EDL) of a spacecraft is one of the more dynamically complex phases of any lander mission. Nonlinearities persist as the spacecraft plummets through the atmosphere, unfurls a parachute, fires retro-rockets, and finally lands (or rebounds) off of the planet's surface. A filter that linearizes these dynamics can quickly diverge if the process noise is not sufficiently or intelligently modeled. Unfortunately, this can lead to excessively large (and misleading) covariance estimates.

Fortunately, a new technique that does not linearize the propagation of the state or covariance has been developed, the unscented Kalman filter (UKF) [2]. To propagate the state and covariance, the UKF samples the covariance around the mean state. Those points are then propagated through the equations of motion, *which could vary depending on the state.* A weighted average of the propagated points constitutes the predicted mean, and the predicted covariance is based on the dispersion of the propagated points. The measurement is modeled by taking the weighted average of the measurement modeled as a function of each set of points. The dispersion of the measurement models is then used to make the measurement covariance. A cross-correlation matrix is created using the dispersions of the modeled states and the modeled measurements. No Jacobians or Hessians have been taken, but there is no need. All that the UKF needs to compute a gain and an update has already been calculated.

An qualitative example of the UKF over the EKF follows: an airbag lander that bounces could be modeled using two sets of equations of motion (EOM): simple free-fall before the bounce, and a spring-mass-damper during the bounce. In a traditional extended Kalman filter (EKF), this transition might be modeled using some kind of threshold based on height, or use both sets of EOMs and weighting them based on the height above the surface. The latter strategy can become very complex, while the former strategy is perhaps too simple. Additionally, a linearized covariance could falsely indicate that half of the possible solutions lie below the surface. The UKF handles this by applying the SMD equations of motion to those points that are below the threshold and the free-fall equations of motion to those points above. Consequently, the possibility of the position existing below the surface is reduced, since the covariance is now a function of the SMD equations of motion.

The author is part of a team of engineers who are tasked with developing a tool that reconstructs the EDL of the Mars Exploration Rover spacecraft and lander. The reconstruction is of the trajectory and attitude (6-DOF) using radar altimetry and data from a single IMU. Previous 6-DOF reconstruction work of the MER airbag drop tests using an EKF, multiple accelerometers, and a gyroscope have proven the concept [3]. However, the EKF in that work diverged if large amounts of process noise were not added. Adding this process noise led to excessive uncertainty in the estimate. Continued work (unpublished) using one accelerometer and one gyroscope showed that the EKF diverged unless even greater levels of process noise were added. The uncertainty of the estimate was forced to exceed pragmatic or practicable levels.

This paper presents results of a EDL reconstruction using simulated data in an UKF. The UKF includes dynamics models of the entry, descent (presented in [1]) and landing (presented in this paper). The data used in the filter are from EDL simulations of the MER spacecraft and lander. The performance of the UKF in reconstructing the EDL is compared to the EKF. Previous entry examples have shown the UKF to have better convergence and better accuracy that the EKF using simulated range data [2]. This paper will outline UKF strategies and possibilities for reconstructing the EDL of the upcoming MER mission.

References

[1] Lisano, M.E., "An EKF to Reconstruct MER Entry and Descent," *abstract submitted to 13th AAS/AIAA Space Flight Mechanics Meeting, February 9-12, 2003, Ponce, Puerto Rico.*

[2] Julier, S.J. and J.K. Uhlmann, "A New Extension of the Kalman Filter to Nonlinear Systems," *Proceedings of the SPIE, Volume 3068, SIgnal Processing, Sensor Fusion, and Target Recognition VI*, edited by I. Kandar, Orlando Florida, April 1997, pp. 182-193.

[3] Wawrzyniak, G.G. and M.E. Lisano, "Using Inertial Measurements for the Reconstruction Of 6-DOF Entry, Descent, and Landing Trajectory and Attitude Profiles," *AAS/AIAA Space Flight Mechanics Meeting*, San Antonio, Texas, February 2002.

Condensed Abstract

The entry, descent, and landing (EDL) of a spacecraft is one of the more dynamically complex phases of any lander mission. A filter that linearizes these dynamics can quickly diverge if the process noise is not sufficiently or intelligently modeled. A technique (unscented Kalman filtering) that does not make linearizations of the dynamics is presented and compared to traditional filtering techniques (extended Kalman filtering). Simulated data from the MER spacecraft and lander are used to validate the filter.