Center of Gravity and Velocity Estimation of an Unknown Orbiting Object from Optical Flow

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In spacecraft proximity operations and missions, such as on-orbit servicing, formation flying, and small bodies exploration, on-board vision based techniques are required for autonomous relative navigation of a chaser spacecraft with respect to a target object because ground-based communication is inefficient due to delays and lack of coverage. These techniques are grouped under the general problem of spacecraft pose estimation. Successful pose estimation provides the relative position and orientation of a target object with respect to the chaser spacecraft. In this project, we improved upon a portion of the monocular based pose estimation system for such targets with the idea that monocular based systems offer a solution with low mass, volume, and power consumption. We developed an Extended Kalman Filter based algorithm that utilizes an alternative derivation of optical flow to estimate the center of gravity and the relative velocity of a moving target with respect to a moving chaser. These values form a part of the overall pose of the target as required by the goal of spacecraft pose estimation.

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Introduction

In spacecraft proximity operations and missions, such as on-orbit servicing, formation flying, and small bodies exploration, on-board vision-based techniques are required for autonomous relative navigation of a chaser spacecraft with respect to a target object because ground-based communication is inefficient due to delays and lack of coverage.

These techniques are grouped under the general problem of spacecraft pose estimation.

In this project, we improved upon a portion of the monocular based pose estimation system for such targets with the idea that monocular based systems offer a solution with low mass, volume, and power consumption.

Methods

We developed an Extended Kalman Filter based algorithm that utilizes an alternative derivation of optical flow to estimate the center of gravity and the relative velocity of a moving target with respect to a moving chaser. These values form a part of the overall pose of the target as required by the goal of spacecraft pose estimation.

We modeled the center of gravity (CG) filter after a modified optical flow equation:

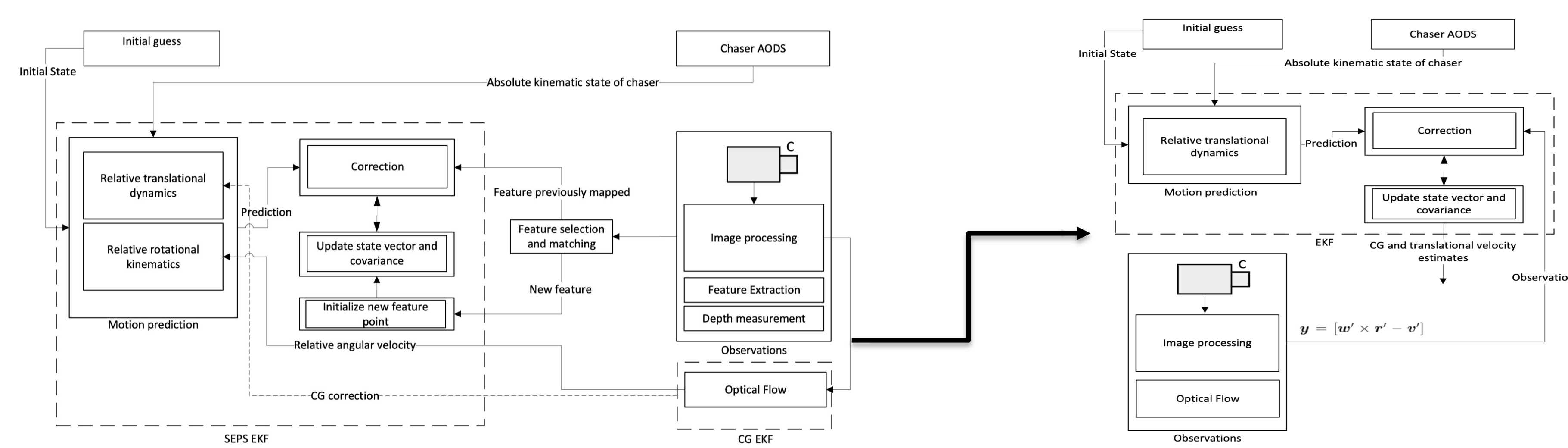
$$\frac{\partial o}{\partial t}\bigg|_{t=0} = \frac{\partial P(p')}{\partial p'}\bigg|_{p'(0)} (\omega_c \times p' + \omega' \times p' - \omega' \times T_0' - v')$$

This optical flow relation takes the movement (rotation and translation) of both the chaser and target into consideration. The state and measurement vectors of the filter are:

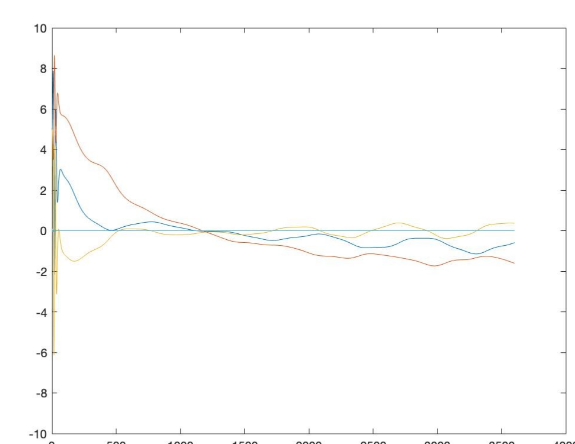
$$\boldsymbol{x} = [\boldsymbol{r}', \boldsymbol{v}'] \qquad \boldsymbol{y} = [\boldsymbol{w}' \times \boldsymbol{r}' - \boldsymbol{v}']$$

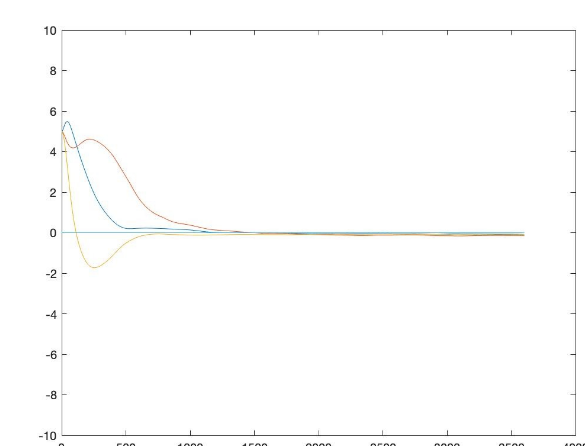
Results

Below are the architectures of the Pose Estimation system and the optical flow based CG estimation sub-system. The CG filter's measurement vector is based on the optical flow relation described in the methods section:



We developed several iterations of the CG filter. Below are the estimation results of the measurement through two approaches. These simulations run for 3600s with a time step of 1.00s, so there are 3600 data points. Each data point represents the difference between the real CG value and the estimated CG value, so the plots represent error of the estimation.





The first figure is based on a basic identity covariance matrix, and the second figure is the improved filter based on the least squares estimation method.

The results of CG estimation for both methods start with similar levels of errors, however the least squares method's error decreases more as time goes on. To get an estimate of improvement, we averaged the norm of the error vector of the state simulations with three simulations and found the decrease in error to be an average of ~60%.

Conclusions

We have developed and improved the optical flow-based CG filter to estimate the CG and velocity of moving targets with respect to moving chasers. In combination with the SEPS filter, this CG filter determines the uncooperative target's overall pose.

The next step of the CG filter's development is to modify the state vector of the filter to include the angular velocity of the target. This would require the estimation of the target's inertial matrix and therefore modifying the state and measurement vectors of the filter.

As a result, it would provide us with a filtered estimate of the rotation as opposed to a measurement and as a result, the CG-SEPS system will determine the overall pose of the target more accurately.

References

V. Capuano, K. Kim, A. Harvard, and S.-J. Chung, "Monocular-Based Pose Determination of Uncooperative Space Objects," Acta Astronautica, 2019.

S.A. Van De Geer, "Least Squares Estimation," 2005.

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