Amirkabir Journal of Mechanical Engineering

Amirkabir J. Mech. Eng., 53(10) (2022) 1187-1190
DOI: 10.22060/mej.2021.19629.7074

Modified Variable Structure Estimation and Control for Constrained Landing on Mars

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ABSTRACT: Landing on Mars is one the paramount space missions undergoing various system and environmental uncertainties. Hence an exact model to represent the dynamic system cannot be achieved in advance, and subsequently model-based navigation algorithms degrade. In this regard, the present paper has focused on a robust integrated estimation and control algorithm to attain an accurate navigation in the presence of different uncertainties for the nonlinear problem of landing on Mars. The proposed algorithm has been developed based on the variable structure control framework. This method alleviates limitations of the existing algorithms including the requirement of the Jacobian calculation and the dimension equality for the state and measurement vectors via statistical linearization and the generalized matrix inverse theory, respectively. Performance of the proposed algorithm has been investigated via Monte Carlo simulations in the presence of different uncertainties including atmosphere instability and modeling errors, time delay of actuators, the geometric constraint of the landing site as well as the saturation limitations of actuators. In addition, the obtained results have been compared to those of the well-known extended Kalman filter- PID combination. This comparison proves the superiority of the proposed variable structure estimation and control algorithm in terms of the accuracy and robustness.

Review History:

Received: Feb. 12, 2021
Revised: Jul. 08, 2021
Accepted: Jul. 16 2021
Available Online: Jul. 21, 2021

Keywords:

Robust estimation
Robust control
Landing
Cubature Kalman filter
Variable Structure filter

1. INTRODUCTION

Space exploration and landing on other planets are significant missions attracted many researchers in recent decades. However, the system dynamics cannot be forecasted accurately in such space missions due to vast variations of the environmental characteristics and system uncertainties. As the prevailing algorithms applied to the estimation and control of a lander are model-based, their performance degrades against such inevitable uncertainties. To cope with such a difficulty, robust filters like the augmented state, two-step, and multi-step Kalman filters have been proposed [1]. Adaptive multiple model filer is the other algorithm that employed a bank of Kalman filters with different settings and extra computational burden to this aim [2]. These robust algorithms are ineffective against nonlinear dynamics and suffer from model linearization. Control algorithms adopted for the landing phase can be classified into three categories of optimal control [3], predictive control [4], and robust control [5] with different cost functions, model accuracy requirements, and computational complexities. The present study has been devoted to addressing the problem of nonlinear and robust integrated estimation and control of a Mars lander. To this aim, a variable structure approach has been adopted as the basic framework. A smooth variable structure filter (SVSF) has been proposed for the estimation of linear systems with Gaussian inputs in 2002 and then extended to nonlinear dynamics in 2007 [6]. Comparison of the SVSF with Kalman filter family and particle filter in presence of uncertainties reveals the stability of the SVSF [7]. To achieve an estimation algorithm that inherits the optimality of Kalman filters and robustness of the SVSF, these two types of filters have been combined [8]. It has been shown that the combination of the Cubature Kalman filter (CKF) and the SVSF, called CK-SVSF, demonstrates a superior performance than other similar combinations. However, the existing CK-SVSF is shaped based on the assumption of a linear measurement model and dimension equality of the state and measurement vectors. Accordingly, the application of the existing CK-SVSF is limited to linear or differentiable measurement systems with the same dimension as the state vector. Addressing these difficulties is the key contribution of the present paper. To this aim, statistical linearization has been substituted for the analytic linearization and a completely nonlinear robust filter is achieved. Sequentially, the filter gain is modified to revise the dimension problem via taking advantage of the generalized matrix inverse theory. The modified CK-SVSF has been integrated into a sliding mode control and then applied to the estimation and control of a Mars lander in the presence of modeling error, the geometric constraint of the landing point, saturation, and delay of actuators. In addition, this integrated algorithm is compared to the well-known combination of the Extended Kalman Filter (EKF)-Proportional–Integral–Derivative (PID) algorithm.

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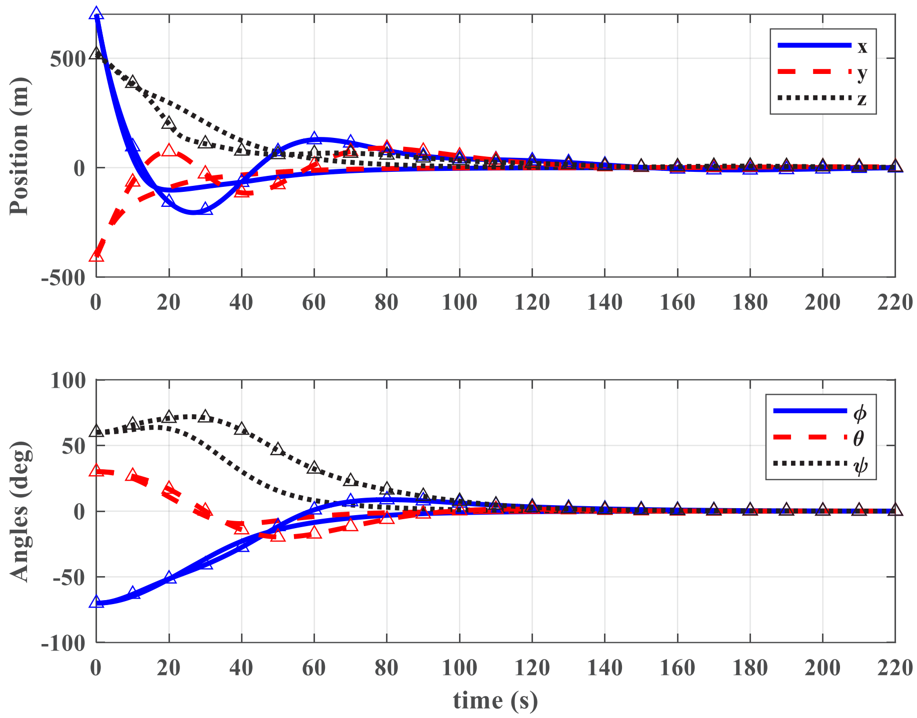

Fig. 1. Time history of the position vector and Euler angles- triangles denote the EKF-PID method results

2. ROTO-TRANSLATIONAL DYNAMICS

Position and attitude of the assumed rigid Mars lander are represented by the Euler angles (φ, θ, ψ) and topocentric Cartesian coordinates (x, y, z), respectively. Gravity ($\boldsymbol{g}$) and aerodynamic drag ($\boldsymbol{D}$) [9] are considered to describe the lander dynamics in the body coordinate system. Therefore, rotational and translational motions are described respectively as:

$$\dot{\boldsymbol{\omega}} = J^{-1}(\boldsymbol{M}_{dist} + \boldsymbol{M}_{Actuator} - [\boldsymbol{\omega}\times]J\boldsymbol{\omega}) \tag{1}$$

$$\dot{\boldsymbol{v}} = -[\boldsymbol{\omega}\times]\boldsymbol{v} + \boldsymbol{g} + \frac{\boldsymbol{D}}{m} + \frac{\boldsymbol{F}_{Actuator}}{m} \tag{2}$$

Where $\boldsymbol{\omega}$ represents the angular velocity vector in the body coordinate system, J is the moment of inertia matrix, and $\boldsymbol{M}_{dist}, \boldsymbol{M}_{Actuator}$ denote the disturbance and control moments, respectively. $\boldsymbol{v}$ is the translational velocity, and m refers to the lander's mass. $\boldsymbol{F}_{Actuator}$ is the control force as well. The terrestrial constraint of the landing point is modeled as a cone with a limited half angle.

3. ESTIMATION AND CONTROL

Sliding Mode Control (SMC) [10] has been exploited here to regulate the state vector as follows,

$$\boldsymbol{M}_{Actuator} = [\boldsymbol{\omega}\times]J\boldsymbol{\omega} - J\Lambda_{att}\dot{\boldsymbol{\Theta}} - JK'_{att}sign(S_{att}) \tag{3}$$

$$\boldsymbol{F}_{Actuator} = m[\boldsymbol{\omega}\times]\boldsymbol{v} - m\boldsymbol{g} - m\Lambda_{pos}\dot{\boldsymbol{r}} - mK'_{pos}sign(S_{pos}) \tag{4}$$

Where $\boldsymbol{\Theta}$ is a vector standing for the Euler angles, $S_{att} = \boldsymbol{\omega} + \Lambda_{att}\boldsymbol{\Theta}$ and $S_{pos} = \boldsymbol{v} + \Lambda_{pos}\boldsymbol{r}$ are sliding surfaces. $\Lambda_{att}, \Lambda_{pos}, K'_{att}$, and K'_{pos} are gain matrices. To modify the existing CK-SVSF [8], the measurement Jacobian matrix (H) has been replaced as follows according to the statistical linearization approach:

$$H = P^{xz\;T}_{k|k-1} P^{xx\;-1}_{k|k-1} \tag{5}$$

Where $P^{xz}_{k|k-1}$ and $P^{xx}_{k|k-1}$ are the prior cross-covariance and state estimation error covariance matrices, respectively. To cope with the dimensional difficulty of the algorithm, the generalized matrix inversion lemma has been utilized to calculate H^{-1} in filter gain formulation,

$$H^{-1} = (H^T H)^{-1} H^T \tag{6}$$

4. NUMERICAL SIMULATION

The performance of the proposed robust variable structure estimation and control algorithm is investigated through 100

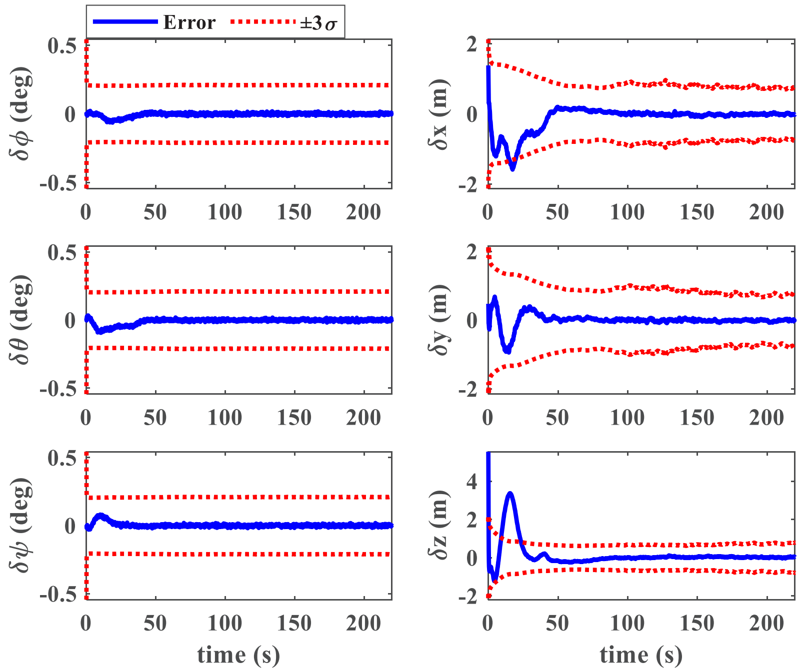

Fig. 2. Position vector and Euler angles estimation error in ±3σ bounds

Monte Carlo simulations. Aerodynamic force and moment are ignored in the estimation and control process to insert a high modeling error in simulations. The time history of the controlled position and attitude is depicted in Fig. 1, where a faster convergence rate of the proposed method than the EKF-PID is demonstrated. The time history of the state estimation errors in $\pm 3\sigma$ bounds is also illustrated in Fig. 2. This Figure confirms the stochastic stability and accuracy of the estimation algorithm.

5. CONCLUSION

Integrated estimation and control of a Mars lander are investigated in the presence of the various system, and environmental uncertainties. In contrast to the existing widespread model-based estimation and/or control methods, the adopted variable structure approach has been founded based on the stability criterion. The proposed algorithm is a combination of a smooth variable structure filter modified for addressing nonlinearities and dimension difficulties plus the sliding mode control. Numerical simulations demonstrate the superiority of the proposed algorithm with respect to the extended Kalman filter-PID combination.

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HOW TO CITE THIS ARTICLE

M. Kiani, R. Ahmadvand, Modified Variable Structure Estimation and Control for Constrained Landing on Mars , Amirkabir J. Mech Eng., 53(10) (2022) 1187-1190.

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