INTEGRATED TRAJECTORY, ATMOSPHERE, AND AEROTHERMAL RECONSTRUCTION METHODOLOGY USING THE MEDLI DATASET

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ABSTRACT

The Mars Science Laboratory (MSL) mission's instrumentation will enable accurate reconstruction of the vehicle's entry, descent, and landing (EDL) performance including the trajectory, the observed atmosphere, aerodynamics, aeroheating, and heatshield material response. The objective of this paper is to develop methodologies for an integrated approach to the reconstruction of the vehicle's EDL performance. Two estimation approaches are presented: Serial and Concurrent. The serial approach is demonstrated by application to the Mars Pathfinder flight data and estimating trajectory and aeroheating performance.

1. INTRODUCTION

The Mars Science Laboratory mission contains on-board a novel sensor suite that will enable the collection of unique entry, descent, and landing data, which will be highly beneficial for the design of future vehicles. Despite data collected from previous Mars missions, there are still substantial uncertainties in the modeling of the vehicle aerodynamics, thermal protection system (TPS) response, and the atmospheric and aeroheating environments of the EDL vehicles. The MSL Entry, Descent, and Landing Instrumentation (MEDLI) contains sensors that can improve the identification of these modeling uncertainties and may advance the state-of-the-art analysis tools by reducing these uncertainties. However, since there exists uncertainties in the engineering and design models themselves, traditional reconstruction methodologies for trajectory and aerothermodynamic analyses have to be augmented to effectively utilize the MEDLI data to inversely estimate the parameters of interest. This paper presents methodologies to reconstruct trajectory and aerothermal parameters of interest from the MEDLI dataset. Emphasis is on the coupling between the trajectory and aerothermal reconstruction so that the entire MEDLI dataset can be leveraged to reconstruct a complete picture of MSL's states.

2. MEDLI AND ESTIMATION APPROACH

MEDLI consists of two sensor suites: the Mars Entry Atmospheric Data System (MEADS), which provides direct measurement of stagnation pressure distribution on the entry body, and the MEDLI Integrated Sensor Plug (MISP), which will provide sub-surface temperature profiles of the TPS and isotherm depth measurements at different locations of the heatshield [1]. The sensors are placed on the heatshield (see Fig. 1) to record pressure and temperature profiles during the hypersonic and supersonic phase of the flight.

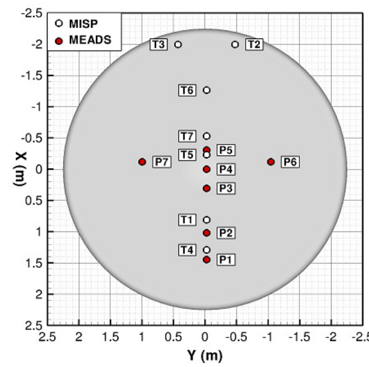


Fig. 1. MEDLI locations. [2]

The MEADS sensors consist of seven transducers (see Fig. 2) strategically placed on the MSL aeroshell to help reconstruct three parameters of interest: angle of attack, sideslip angle, and dynamic pressure. The science objective for MEADS is to reconstruct angle of attack and sideslip angle to within ± 0.5 deg. and dynamic pressure to within ± 2% when the freestream dynamic pressure is above 850 Pa. [1]

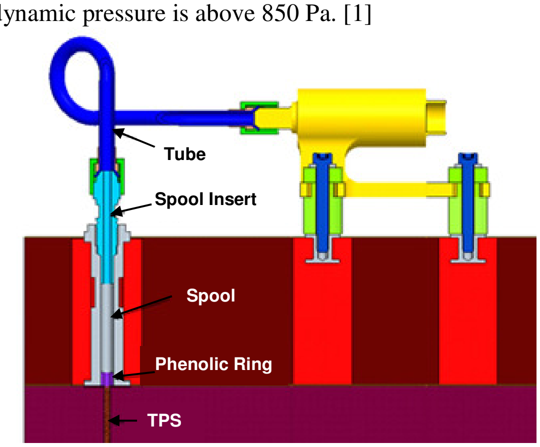
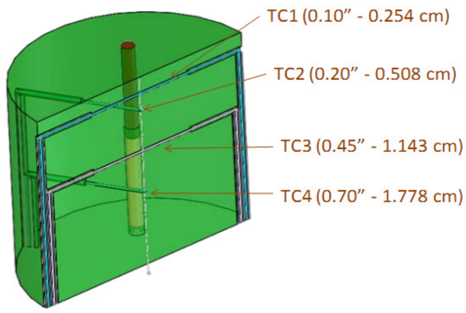
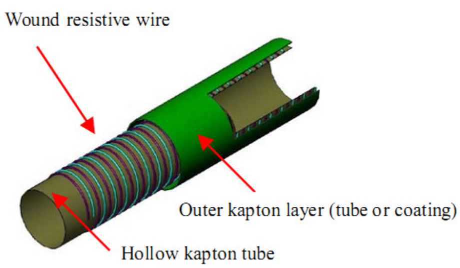


Fig. 2. MEADS configuration. [3]

The MISP sensors (see Fig. 3) consist of seven plugs with four embedded thermocouples (TC) each to measure the in-depth temperature history through the heatshield. The plugs are made from the heatshield TPS materials. The Hollow aErothermal Ablation and Temperature (HEAT) sensor measures the progress of a 700 °C isotherm through the TPS during entry and descent.



(a) MISP Plug [4]



(b) HEAT sensor [5]

Fig. 3. MISP configuration.

The data from both sensor suites, together with other on-board sensors like the inertial measurement unit (IMU) and the radar altimeter, will allow the reconstruction of the flight trajectory, atmospheric and aerothermal environment, and the TPS material response and flight aerodynamics parameters. Traditionally, the reconstruction process for the trajectory has been separate from the estimation of heating and TPS material response parameters.

However, since in reality there is some coupling between the trajectory and aerothermodynamics of the vehicle, this paper demonstrates two approaches where this coupling is used to reconstruct parameters of interest using the entire MEDLI dataset at the same time. The first approach, termed *serial* reconstruction, utilizes a very loose coupling between MEADS and MISP reconstruction. The second approach, called *concurrent* reconstruction, attempts to estimate both trajectory and heating parameters simultaneously in a format where there is very close coupling between MEADS and MISP data. The reconstruction of EDL trajectory and heating parameters in an integrated fashion has received little attention in literature, so these methodologies are very novel to this field.

3. SERIAL RECONSTRUCTION

Serial reconstruction technique consists of doing the trajectory and atmosphere reconstruction first, and then using these estimated quantities for aerothermal and TPS material response parameter estimation. Fig. 4 shows the flow of information in this reconstruction process. The link between the trajectory and atmosphere reconstruction and the aerothermal and TPS response reconstruction is served by a nominal heating environment that is generated using Computational Fluid Dynamics (CFD) and the estimated trajectory and atmosphere.

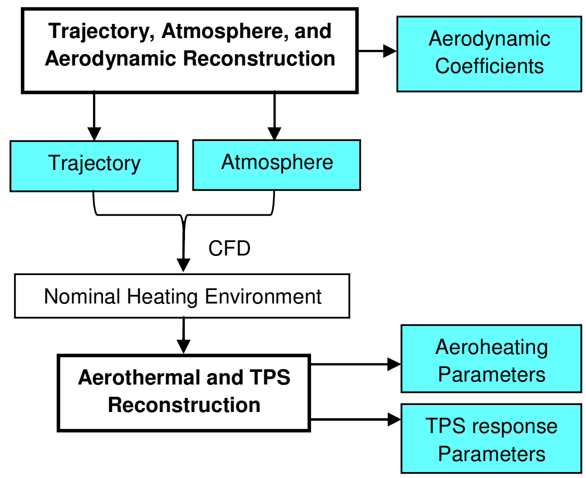


Fig. 4. Flow diagram of serial reconstruction.

Serial reconstruction process keeps the trajectory, aerothermal, and material response parameter estimation process independent of each other. Although CFD provides a loose coupling between the two estimation procedures, on the whole the two processes are separate from each other and can thus use tried and tested methods in the fields of trajectory and state estimation and heating-related Inverse Parameter Estimation (IPE). The individual parts of the serial reconstruction methods are described below.

3.1 Trajectory, atmosphere, and aerodynamic reconstruction

Trajectory reconstruction for the MEADS dataset is done using a *statistical* estimation algorithm that creates an initial guess of the trajectory states using equations of motion and then corrects the guessed states using the data from the sensors, namely IMU, radar altimeter, and the MEADS pressure measurements. The state variable for the estimator can be augmented to include atmospheric parameters in addition to trajectory states. Finally, the reconstructed results can be used to calculate the aerodynamic coefficients, especially if IMU data is available. Fig. 5 shows the flow of information for the trajectory, atmosphere, and aerodynamic reconstruction.

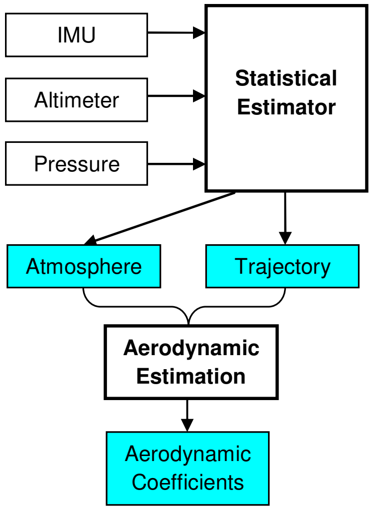


Fig. 5. Flow diagram of the trajectory, atmosphere, and aerodynamic coefficient reconstruction process.

The statistical reconstruction process described above has been demonstrated in the literature [3], [6]-[11] for Mars EDL applications. The statistical estimator of choice has been the Extended Kalman Filter (EKF), which is a non-linear modification of the Kalman filter to estimate mean and variance of the state variable. The EKF propagates the state variable and its variance from the initial condition to the end time using dynamic, process equations (equations of motion and equations of state for trajectory and atmospheric parameters). The propagated state is adjusted at each time there is data available by the EKF using a combination of the uncertainty of the data and the residual between the data and predicted measurements based on currently estimated states. Ref. [11] also uses an Unscented Kalman Filter (UKF) since UKF has been shown in literature to have better state and uncertainty estimation capability than the EKF.

Usually, the data is processed in a forward direction, i.e. the estimation process starts from atmospheric interface and progresses until touchdown. However, the estimate of the states can be improved if the data is also processed in a backward direction, i.e. starting the estimation from touchdown and progressing to atmospheric interface. The backward run starts at the end of the forward run and usually has a lower uncertainty (and higher accuracy) in the state estimate. Refs. [8] and [11] shows the details regarding the trajectory reconstruction including the equations of motion, measurement models, and the estimation algorithms.

3.2 Nominal heating environment generation

The next step is to calculate the vehicle's surface heating based on the reconstructed trajectory and atmosphere. This nominal aerothermal environment will serve as an initial guess for the aerothermal and TPS reconstruction effort. It also provides a baseline to which the reconstructed environments can be compared. The surface heating is characterized by many parameters and not all of these parameters can be estimated simultaneously, but nominal heating environment calculation will provide improved baseline values for the parameters that will not be estimated. The vehicle's aerothermal environment is calculated using CFD tools such as the NASA code, Data Parallel Line Relaxation (DPLR) [12]. The CFD simulations is performed on a subset of the reconstructed trajectory points.

3.3 Aerothermal and TPS material response reconstruction

In the direct design approach, once the surface heating boundary conditions are calculated using CFD, a material response code such as NASA's Fully Implicit Ablation and Thermal response (FIAT) [13] program is used with the TPS material properties to calculate the thermal response of the heatshield. However, there are substantial uncertainties associated with both surface heating prediction and TPS material response; thus, simultaneous estimation of all these parameters from flight data is not possible. For the analysis of MEDLI data, the "TC Driver" approach is used to address the estimation of both surface heating and material properties. Fig. 6 shows a diagram of aerothermal and TPS reconstruction methodology using this approach.

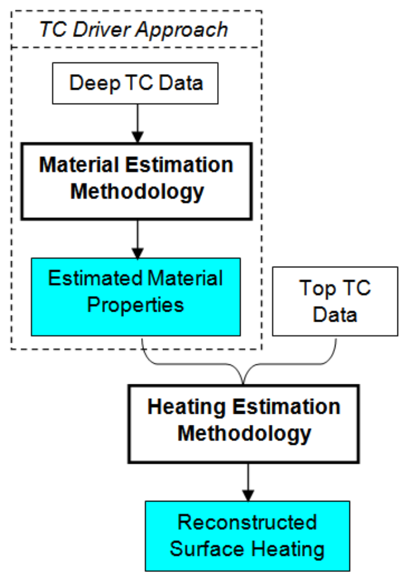


Fig. 6. Flow diagram of the aerothermal and TPS reconstruction using the TC driver approach.

In the TC driver approach, the surface heating problem is decoupled from the in-depth heat transfer problem by using the data from the top TC as the boundary condition and the solving the simpler heat conduction problem for the TPS block below that TC. This way temporarily one can eliminate the surface boundary conditions and their effect on the material response below the top TC and then estimate material properties from the remaining deeper TC data using IPE methods. These methods estimate the material properties by minimizing the difference between thermal response predictions and the flight data [14], [15]. Ref. [16] introduces a methodology where Monte Carlo and sensitivity analyses are used to determine what material properties need to and can be estimated from the TC data.

Once the material properties are updated with a new estimate, the normal ablation problem can be solved and the top TC data is used to estimate the surface conditions using inverse methods. For an ablative material, many complex physical and chemical processes occur at the surface. Therefore, the surface heating is characterized by many time-dependent parameters such as convective heat transfer coefficient, C_H, recovery enthalpy, H_R, and other parameters characterizing surface ablation. As not all of these parameters can be reconstructed concurrently, in this study, only the surface heat transfer coefficient is estimated, as it is the most dominant parameter characterizing the incoming convective heating. Once the C_H profile is reconstructed, the associated net surface heat rate can be calculated from the other parameters. Ref. [17] explains the inverse methods used for heating estimation and investigates their performance using simulated MISP data. The Gauss-Newton whole-time domain, least-squares method in conjunction with Tikhonov first-order regularization technique is applied to the problem [18], [19].

The methodology proposed here only employs the TC data. The isotherm sensor is undergoing a testing and calibration program to better characterize its performance and thus HEAT data is not used in this analysis. In the future, the results of these calibration tests will enable TPS recession estimation from flight data. The isotherm sensor can then be also used as an independent verification of the TC data.

4. CONCURRENT RECONSTRUCTION

The concurrent reconstruction process requires a mechanism to estimate trajectory-related parameters and aeroheating-related parameters at the same time. Typically, trajectory and atmosphere parameters are estimated using a state estimation algorithm, i.e. the estimation requires dynamic, process equations [20], while aerothermal parameters usually cannot be described by dynamical equations but are still functions of the atmospheric and trajectory states. Therefore, an integrated reconstruction algorithm still has to maintain the coupling between trajectory, atmosphere, and aeroheating parameters.

Inverse state and parameter estimation algorithms can be loosely classified into two categories: sequential in time approach (the estimate progresses by processing one measurement at a time) or a whole-time domain approach (all measurements are processed together as a batch at the same time). As described earlier, the literature does not contain a lot of information about doing concurrent trajectory, atmosphere, and aeroheating-related reconstruction. However, this paper proposes two types of concurrent estimation methodologies to specifically reconstruct MEDLI-type data. Each of the two methods utilize the general nature of traditional sequential in time and whole time-domain type of estimation methods to construct a methodology suited for the unique datasets of the Mars EDL reconstruction problem.

Unfortunately, a caveat of this type of reconstruction methodology is that the aerodynamic coefficient reconstruction and the TPS material property estimation cannot be in the loop and that these two types of parameters have to be estimated off-line. The TPS material properties can be reconstructed using the TC Driver approach described in an earlier section. Then this updated TPS material response model can be used for the aerothermal reconstruction in the concurrent reconstruction method. The aerodynamic coefficients can be calculated at the end of the concurrent reconstruction method using the estimated trajectory and atmosphere.

The sequential in time approach to concurrent reconstruction is described below in Fig. 7. The dynamic equation section of the methodology consists of equations of motion to propagate trajectory and atmospheric states [9]. This process will appear in the whole time-domain approach as well, but in this case, the propagation occurs over a small time frame between two measurements (the times are denoted here by the index k). The propagated trajectory and atmosphere can be used to generate a nominal heating environment. Typically, CFD simulations are used in this step to generate the heating environment, but for concurrent reconstruction techniques, this process has to be expedited. Thus, NASA-developed engineering tools, such as the Configuration Based Aerodynamics (CBAERO) model [21], anchored to *a priori* generated CFD points can give a nominal estimate of the heating environment.

Next, the nominal estimate of the states will be used together with measurement models and simulations to generate predicted measurement values for the MEADS, MISP, IMU, radar altimeter data. The MISP data is generated using the FIAT tool described earlier. Note that the models for the trajectory states and aeroheating states are decoupled at this point.

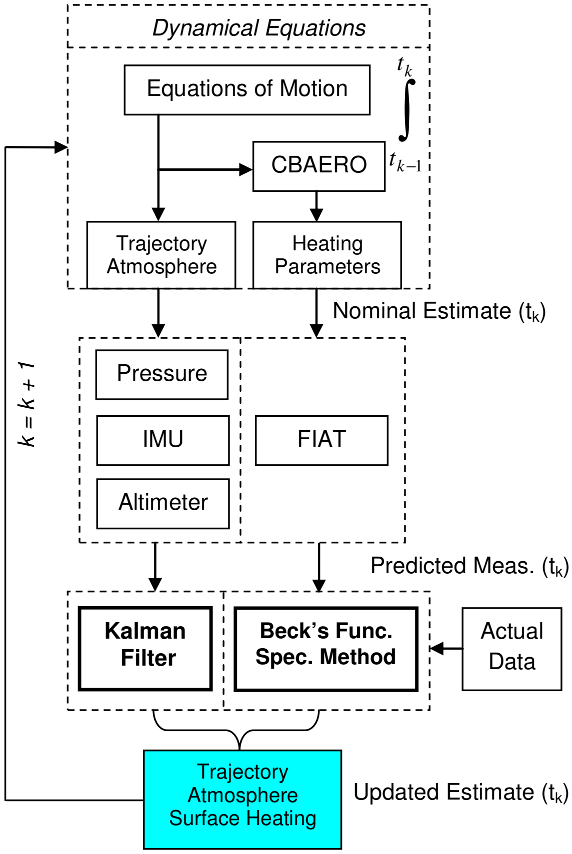


Fig. 7. Flow diagram of the sequential in time technique of concurrent reconstruction.

The inverse analysis methods for the two types of states are also different in this case. The trajectory and atmospheric states can be reconstructed sequentially by using a statistical estimation algorithm, such as Kalman filters [9], as described in an earlier section. The aeroheating parameters are reconstructed using a sequential estimation methodology proposed by Beck et al. [18], called the function specification method. Specifically, Beck's future-time algorithm will be used for the estimation of surface heating conditions from the TC data. This method estimates surface heating at any given time using measurements from a specified future time window. The number of future time steps used in this process will determine the level of regularization used. Similar to Kalman filtering techniques, this method is sequential in nature and fits well within the sequential, concurrent estimation methodology proposed here.

The flow diagram of the whole-time domain approach to concurrent reconstruction is shown in Fig. 8. The dynamical equations are now used to provide a nominal estimate of the trajectory and atmosphere for the whole time frame of the dataset and this estimated trajectory and atmosphere is used with CBAERO to create a nominal heating environment for the whole trajectory. However, for the whole-time domain approach, this step is only conducted once. The initial nominal estimate of the states are used to generate predicted measurement values and then a least-squares filter (batch-type filter in estimation theory literature) uses the predictions and the actual data to reconstruct both the trajectory and aeroheating states at the same time. The estimated trajectory and atmosphere are used in conjunction with CBAERO to update the non-estimated heating parameters, such as recovery enthalpy, while the estimated heating parameters, like surface heat transfer coefficient, are updated by the least-squares filter not CBAERO. All of the estimated parameters are then fed back into the measurement models and the process is continued until the residual between the predicted and actual data converges.

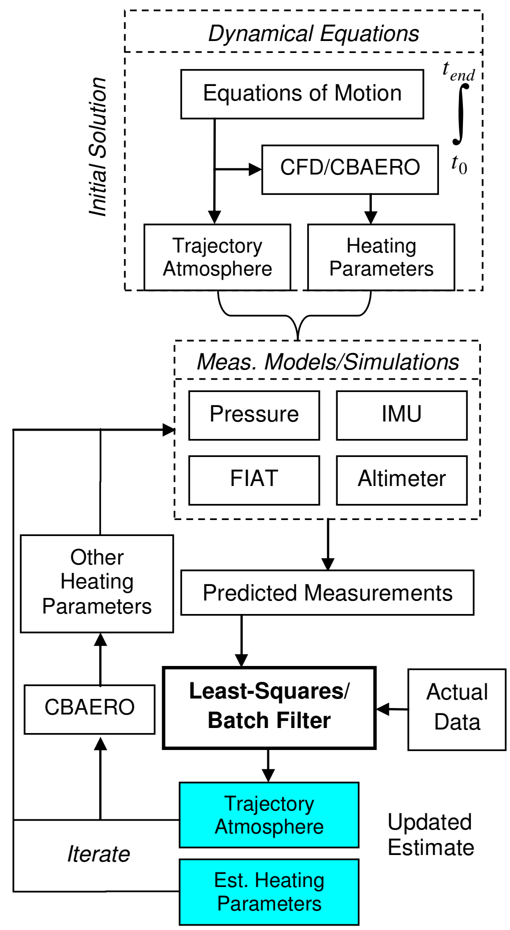


Fig. 8. Flow diagram of the whole-time domain technique of concurrent reconstruction.

The concurrent reconstruction methodology tries to bridge the divide between state estimation methods used for trajectory reconstruction and parameter reconstruction techniques traditionally used for aeroheating reconstruction. Approaches similar to the methods described in this section are rare in the literature, so it is unknown how well the two methods will fare for an actual reconstruction process. However, due to the coupling between trajectory and aeroheating that exists in real life, it is hoped that preserving the coupling in the estimation methodology will allow for an improved reconstruction from the MEDLI data. Unlike the serial reconstruction methodology, the concurrent methodology has not been implemented for a simulated or an actual dataset. Work is currently being conducted so that this methodology can be used for the actual MEDLI dataset reconstruction.

5. SERIAL RECONSTRUCTION RESULTS – MARS PATHFINDER

Due to the unavailability of the actual MEDLI data at the time of the publication of this paper, the serial reconstruction methodology is demonstrated using the Mars Pathfinder dataset. Unlike MSL, Pathfinder did not have a MEDLI dataset. However, it did have an on-board IMU and radar altimeter and the vehicle contained instrumentation that provided measurements of the SLA heatshield subsurface temperature at different locations. Thus, there is enough information to reconstruct the vehicle's trajectory and Mars' atmosphere on day of the flight and then use this information to reconstruct the aeroheating conditions using the temperature profile dataset.

The Mars Pathfinder aeroshell was instrumented with nine type-K thermocouples and three platinum resistance thermometers (PRT) that provided a history of subsurface temperature on the aeroshell. Fig. 9 shows the location of the temperature probes, while Table 1 summarizes the vehicle entry state used for the trajectory reconstruction. See Refs. 6 and 23 for more details regarding Pathfinder's EDL sequence.

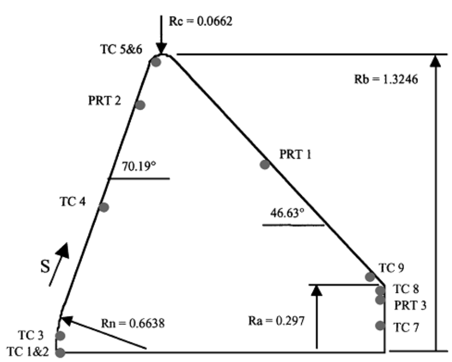


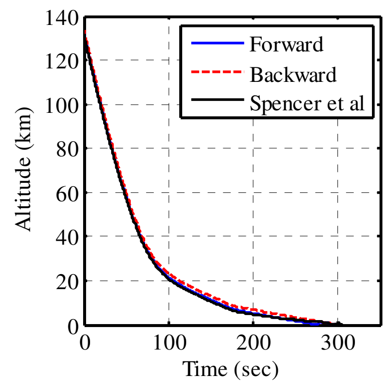
Fig. 9. The locations of the nine thermocouples (TC) and three PRTs on the Mars Pathfinder aeroshell [22].

Table 1. Mars Pathfinder entry state [23].

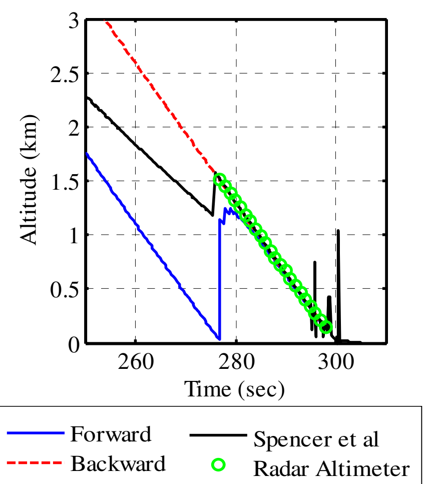
State	Value
Radius	3522.2 km
Areocentric latitude	22.6303 deg.
Longitude	337.9976 deg.
Velocity (inertial)	7.2642 km/s
Flight-path angle (inertial)	-14.0614 deg.
Azimuth angle (inertial)	253.1481 deg.

5.1 Trajectory reconstruction results

The reconstructed altitude history of Mars Pathfinder is shown below in Fig. 10. Reconstruction results from the work of Spencer et al. [23], a NASA reconstruction, has been included for comparison. As mentioned before, the trajectory reconstruction methodology used in this paper processes the flight data in forward and then in a backward direction. The ensuing difference in the altitude profile is clearly visible in Fig. 10b. The Mars Pathfinder dataset consisted of IMU data from entry to landing as well as more accurate (i.e. with less measurement uncertainty) radar altimeter information near the landing site. Hence, one can see a sharp discontinuity in the estimated altitude of the forward run and the Spencer et al. estimate when the radar altimeter information becomes available. This discontinuity is of course not physical, and thus the backward estimate provides a smoother and more believable (and probably more accurate) time history for Pathfinder's altitude since it improves upon the estimate of the forward run.



(a) Altitude



(b) Zoomed-in view of altitude

Fig. 10. Altitude above landing site for Mars Pathfinder.

Fig. 11 shows the estimated velocity and Fig. 12 shows the estimated flight-path angle by the backward run and Spencer et al. There is a negligible difference in the estimated states between the two sources.

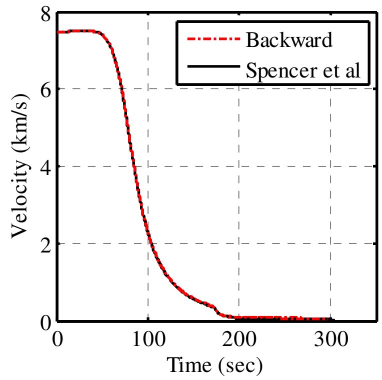


Fig. 11. Atmosphere-relative velocity history for Mars Pathfinder.

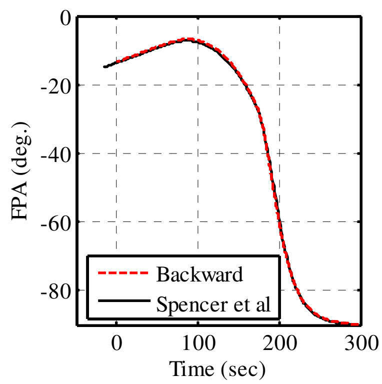


Fig. 12. Atmosphere-relative flight-path angle for Mars Pathfinder.

The day of flight atmospheric conditions for this dataset were not calculated in the statistical filter since Pathfinder did not have a MEADS-type dataset. Hence, traditional atmosphere reconstruction process, where aerodynamic force coefficient knowledge is assumed to be known, was used to estimate the atmospheric density. Ref. [9] explains in detail how such atmospheric reconstruction was done in lieu of MEADS-type dataset. The estimated atmospheric density is compared in Fig. 13 with an independent reconstruction conducted by the Mars Pathfinder Atmospheric Structure Investigation/Meteorology (ASI/MET) program [24]. The two estimated densities compare very well with each other. Note that both reconstructions end at an altitude well before the landing location. This is due to the high uncertainty of the parachute drag coefficient, which in turn deteriorates the density calculation, and is discussed in detail in Ref. [9].

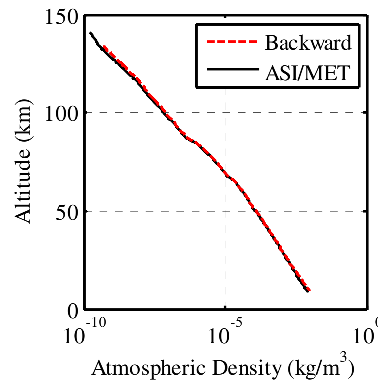


Fig. 13. Freestream atmospheric density for Mars Pathfinder.

5.2 Aerothermal environment prediction

Milos et al. [21] performed CFD calculations and heatshield material response analysis for the Pathfinder vehicle and compared their TPS thermal response results directly to the flight data. No inverse reconstruction based on the flight data was attempted by that study. Mahzari et al. [25] conducted new CFD simulations and material response using updated CFD tools and ablation models. In addition to a direct comparison to the flight data, they performed inverse analysis to reconstruct Pathfinder's surface heating from the flight data. The CFD and reconstruction results given in this paper are taken from this study.

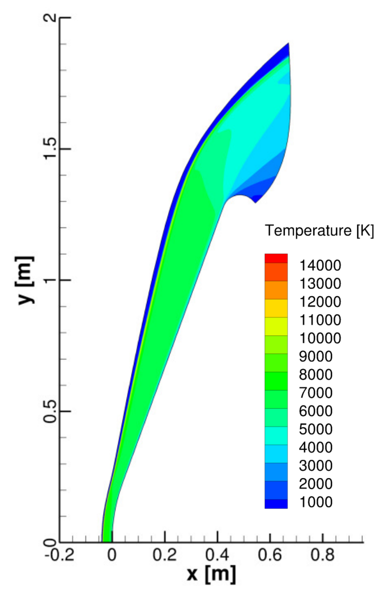


Fig. 14. Pathfinder flowfield temperatures at the peak heating (t = 65 sec).

Pathfinder's nominal aerothermal environment is calculated using the NASA CFD code DPLR based on the reconstructed trajectory shown in the previous section. CFD simulations are performed on a subset of those trajectory points. Fig. 14 and Fig. 15 show the Pathfinder flowfield temperature and surface heat flux at the peak heating time. The simulations were performed both for laminar and turbulent flows. Surface conditions for material response simulations, such as C_H, H_R, and pressure, are extracted from the CFD solutions and are then fitted in time with tight monotonic cubic splines. These surface conditions become inputs to the FIAT material response code that is used in the direct material response calculation and inverse reconstruction. Ref. [25] provides more details on the CFD methodology and results.

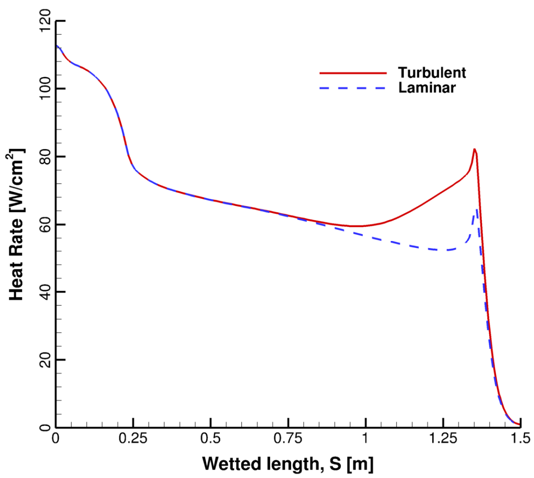


Fig. 15. Pathfinder surface heat flux at peak heating for both laminar and transition to turbulence models.

5.3 Aerothermal reconstruction

The CFD-calculated boundary conditions are used with the material response code to calculate the heatshield in-depth temperatures and are then compared to the flight data. In addition to this direction comparison, an inverse analysis can be performed to reconstruct the surface conditions by minimizing the difference between FIAT predictions and flight data. Ref. [25] explains in details how this inverse analysis was performed for the Pathfinder entry vehicle at the stagnation and shoulder locations. The results shown here are for the stagnation point analysis only.

The TC driver approach proposed earlier for the analysis of MISP data and the reconstruction of both material properties and surface heating cannot be used for the Pathfinder problem. At the stagnation point, Pathfinder had only two TC's: one at the bondline and the other midway through the TPS. The bondline TC measurements did not match the general trend of model predictions and were not used for the inverse analysis (see Refs. [21] and [25]). Only the mid-TPS TC measurements are available for the inverse analysis; therefore, only surface heating reconstruction can be performed and the material properties are assumed to be known and fixed.

As explained earlier, among the parameters that characterize surface heating, only the time-dependent surface heat transfer coefficient profile, C_H, is estimated here while the other parameters are fixed to the calculated values of the nominal CFD results. The estimation is performed using the Gauss-Newton least-squares minimization method in conjunction with Tikhonov regularization technique. These methods are based on the adjustment of the C_H profile in order to minimize an ordinary least-squares objective function, which is equal to the sum of the square of errors between FIAT predictions and flight data. The CFD-calculated C_H profile is first taken as the initial guess and heatshield temperature predictions are calculated using FIAT. Then, the inverse algorithm adjusts the C_H profile in order to minimize the objective function. This process is done iteratively until a good match between the data and FIAT predictions is achieved and a converged C_H solution is obtained. However, inverse problems are ill-posed which results in the presence of non-physical oscillations in the estimated C_H profile [18]. Therefore, regularization techniques are employed to alleviate such oscillations and produce a smooth estimate [19].

Fig. 16-Fig. 18 show the estimation results for the Pathfinder's stagnation location. The red trace shows the prediction from the nominal CFD heating environments, while the blue traces show the predicted measurements corresponding to the inversely reconstructed heating environment. In Fig. 16, it can be observed that the FIAT predictions based on the nominal CFD environments follow the general trend of the flight data but have slightly over predicted values than the measured temperatures. It is clear that C_H inverse estimation provides a much closer match between the data and FIAT predictions.

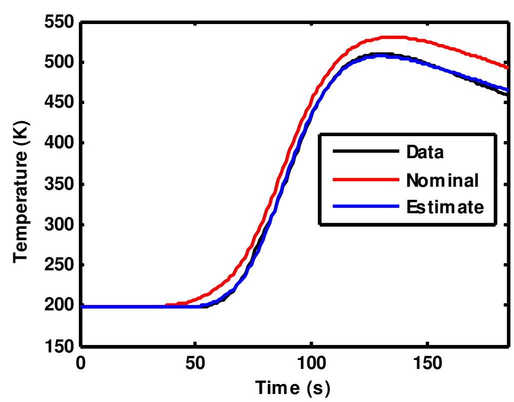


Fig. 16. Pathfinder's stagnation FIAT predictions compared to the data for the nominal and inversely estimated heating environments.

Fig. 17 shows the residual of the nominal and inverse estimate FIAT temperatures with respect to the flight data. It can be observed that the error after C_H estimation has been reduced to within 7 K as compared to the original 35 K.

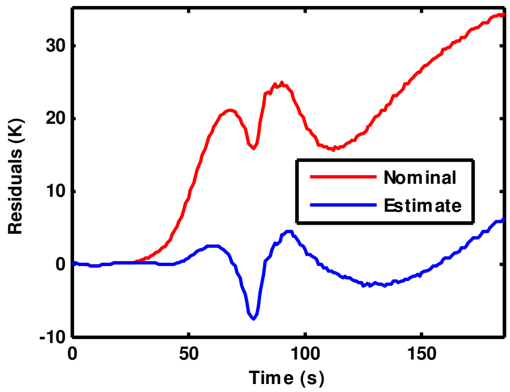


Fig. 17. Residual of FIAT temperature predictions with respect to flight data.

Fig. 18 illustrates the reconstructed C_H profile compared to the nominal CFD-calculated profile. The close match between the data and thermal response code predictions is achieved by reducing the pre-pulse and post-pulse C_H to very small values while slightly increasing the peak. This makes intuitive sense as CFD tools are generally accurate in the pulse regions but not necessarily in the off-pulse regions. See Ref. [25] for a more in-depth discussion about the aerothermal analysis results.

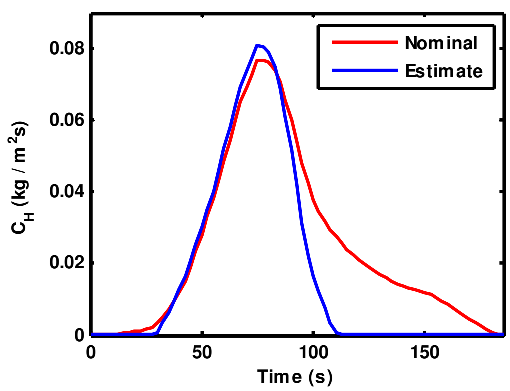


Fig. 18. The reconstructed C_H profile for the Pathfinder vehicle's stagnation location.

6. FUTURE WORK

The methodologies developed in the paper will be applied to the MEDLI data after MSL lands on Mars in August 2012. In the short term, the serial approach to MEDLI reconstruction will be pursued. The trajectory, atmosphere, and aerodynamics coefficients will be reconstructed first from MEADS, IMU, and radar altimeter data and then these results will be passed on to CFD methods to calculate the vehicle's nominal heating. That nominal prediction will be then used in conjunction with the MISP data and inverse methods to reconstruct TPS material response parameters and vehicle's aeroheating environment using the TC driver approach proposed in this paper. The concurrent estimation approach will be the focus of further future research by the authors.

7. CONCLUSIONS

This paper proposes methodologies to reconstruct trajectory and aerothermal parameters of interest in an integrated fashion from the MEDLI dataset. Such integrated reconstruction approach has received little attention in the literature and the coupling between trajectory and aerothermal reconstructions has been typically ignored. In this paper, methods have been developed that take advantage of this coupling so that the entire MEDLI dataset can be leveraged to reconstruct a complete picture of MSL's states. Two integrated reconstruction methodologies are presented. The first approach, termed serial reconstruction, utilizes a very loose coupling between MEADS and MISP reconstruction. The second approach, called concurrent reconstruction, attempts to estimate both trajectory and heating parameters concurrently in a format where there is very close coupling between MEADS and MISP data. The serial approach is demonstrated by application to the Mars Pathfinder flight data. The results for this analysis showed that both trajectory and aeroheating reconstructions can be performed successfully for Mars flight data using the proposed serial approach.

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