A Robustly Stabilizing Model Predictive Control Algorithm

The algorithm can be applied to industrial and automotive systems.

NASA's Jet Propulsion Laboratory, Pasadena, California

A model predictive control (MPC) algorithm that differs from prior MPC algorithms has been developed for controlling an uncertain nonlinear system. This algorithm guarantees the resolvability of an associated finite-horizon optimal-control problem in a receding-horizon implementation. Given a feasible solution to the finite-horizon optimal control problem at an initial time, resolvability implies the ability to solve the optimal control problem at subsequent times.

Originally developed for the control of spacecraft in the proximity of small celestial bodies, the algorithm can also be applied to other systems (such as industrial and automotive systems) for which robust feedback control may be required. The algorithm consists of a feedforward and a feedback component. The feedforward part is computed by the on-line solution of the finite-horizon optimal control problem with the nominal system dynamics, with a relaxation of the initial state constraint at each computation.

The feedback component makes this relaxation possible, which in turn guarantees resolvability and asymptotic stability once an initial feasible solution is obtained at the start of a maneuver. The feedback part involves off-line design of a feedback control policy based on the uncertainty bounds in the dynamical model of the system. Consequently, this algorithm is robust to system uncertainties that are explicitly accounted for in the design of the feedback portion of the control input.

This explicit characterization of the robustness to the uncertainties (which can easily be extended to external disturbances) is particularly desirable in a real-time autonomous control application. Furthermore, the ability to solve for an open-loop trajectory during a maneuver enables model updates (possibly based on real-time information) into the control problem to reduce model uncertainty and improve optimality for the open-loop trajectory. The algorithm has been shown to be robustly stabilizing under state and control constraints with a region of attraction composed of initial states for which solution of the finite-horizon optimal control problem is feasible.

This work was done by A. Behçet Açkmeçe and John M. Carson III of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).

The software used in this innovation is available for commercial licensing. Please contact Karina Edmonds of the California Institute of Technology at (626) 395-2322. Refer to NPO-42754.

Modeling Evaporation of Drops of Different Kerosenes

One model applies to all three classes of hydrocarbon constituents.

NASA's Jet Propulsion Laboratory, Pasadena, California

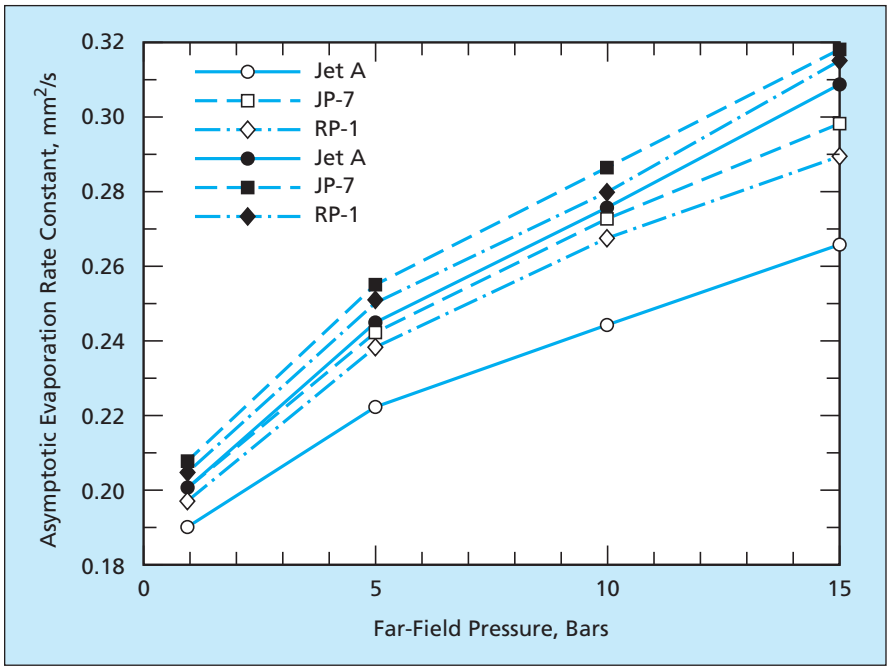
A mathematical model describes the evaporation of drops of a hydrocarbon liquid composed of as many as hundreds of chemical species. The model is intended especially for application to any of several types of kerosenes commonly used as fuels. Like evaporating-multicomponent-fuel-drop models described in several previous *NASA Tech Briefs* articles, the present model invokes the concept of continuous thermodynamics, according to which the chemical composition of the evaporating multicomponent liquid is described by use of a probability distribution function (PDF). However, as described below, the present model is more generally applicable than is its immediate predecessor.

The present model is built on the one reported in "Statistical Model of Evaporating Multicomponent Fuel Drops" (NPO-30886), which appears elsewhere in this issue. To recapitulate: The PDF in that model is a superposition of two functions and, accordingly, is denoted a double PDF. It is a function of the molecular weight plus five other parameters. Unfortunately, some of those other parameters depend on the class of homologous hydrocarbon species, so that it becomes necessary to have a double PDF for each such class entering the fuel composition. The introduction of multiple double PDFs would make the computation very cumbersome, negating the advantage of the continuous-thermodynamics formulation. The derivation of the present model is driven by the concept of a unified thermodynamic representation of three classes of homologous hydrocarbons (alkanes, naphthenes, and aromatics) that constitute the principal components of kerosenes. Somewhat more specifically, it is sought to characterize the hydrocarbons in each homologous series by unified reference temperatures, pressures, and other parameters that depend only on molecular weights and thermodynamic quantities.

The derivation leads to a new version of the double PDF, in which the square root of the molecular weight occupies the position previously occupied by the molecular weight and other parameters are modified accordingly. By design, this version of the double PDF applies to the three major homologous series in kerosene; hence, it is not necessary to use multiple double PDFs. An additional advantage of this formulation is that it is valid over the subcritical region in the pressure range from 1 to 15 bars (0.1 to 1.5 MPa).

The model has been tested on three kerosenes used as aircraft and rocket fuels: Jet A, JP-7, and RP-1. The present

version of the double PDF has been fitted to the discrete species distributions of these kerosenes and extensive calculations of evaporation of isolated drops performed. The results show that under the assumption of a quasi-steady gas phase, a relation known in the literature as the D^2 law (pertaining to the rate of decrease of the square of the drop diameter) is recovered after an initial drop-heating transient. A related quantity known in the literature as the asymptotic evaporation rate constant has been found to be an increasing function of the far-field temperature and pressure, a complex function of far-field composition, and a weak function of the difference between the drop-surface and far-field vapor molar fractions. In a comparison between results obtained (a) under the assumption that the interior of the drop is well mixed (the "wm" assumption) and (b) under the assumption that the drop can evaporate either in a well-mixed mode or at unchanging (frozen) composition (the "wm-fc" assumption), it was found that the differences between the asymptotic evaporation rate constants under the two assumptions is within the range of uncertainty in the transport properties (see figure).



The **Asymptotic Evaporation Rate Constants** of three kerosenes as a function of far-field pressure were computed for a far-field temperature of 1,000 K and zero far-field vapor fraction.

This work was done by Josette Bellan and Kenneth Harstad of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).
NPO-40437