Visualizing a Dusty Plasma Shock Wave via Interacting Multiple-Model Mode Probabilities

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Abstract—Particles in a dusty plasma crystal disturbed by a shock wave are tracked using a three-mode interacting multiple model approach. Color-coded mode probabilities are used to visualize the shock wave propagation through the crystal.

I. INTRODUCTION

MICRON-SIZED “dust” particles suspended in a plasma of neutral molecules, ions, and electrons can be used to model the microscopic kinematics of matter. The dust becomes charged due to collisions with charge carriers in the plasma, resulting in the dust particles interacting via a screened Coulomb force, known as a Yukawa, or Debye-Hückel force [1]. Dusty plasmas can be particularly useful for investigating phase transitions, where a weakly-confined dusty plasma crystal is melted by a shock wave, as considered in this work, and previously in [2], [3]. For a dusty plasma monolayer, single particles can be observed using a digital camera. In the most basic sense, visualizing the dust kinematics consists of processing a sequence of images to reveal the time-varying position of each particle. However, the dust kinematics can be visualized another way — using dynamic-state estimation.

Estimating the state of a moving object based on remote measurements is known as target tracking [4], [5]. In target tracking, a recursive filter that finds the “best estimate” of the dynamic state at each point in time is combined with a decision process for associating measurement data to filter data. In this work, we consider the extended Kalman filter (EKF) [4], which is perhaps the most widely used estimation algorithm for nonlinear systems [6]. The EKF represents a piecewise linearization of nonlinear dynamics about the current estimate. It performs very well if the initial errors in the state estimate are small and the dynamics are approximately linear in the region of state space covered by the errors [5].

The EKF combines the measurement data with state prediction from a dynamical model to produce an estimate which aims to minimize the mean-square error (in target position/velocity/acceleration) at each point in time. The relative weights given to the measurement, and to the prediction, reflect confidence in the accuracy of each. These selectable confidence levels facilitate tuning of the filter design to help optimize the tracker performance. For discussions of EKF design parameters, we refer the reader to [4], [7].

Here we track the position, velocity and acceleration of 3000 simulated dusty plasma particles as an initial crystal lattice is melted by a shock wave that we have induced. This requires the use of three dynamical models, or modes, for predicting the dust dynamics: one each for the “presence”, “absence”, and “aftermath” of the shock wave. Running the corresponding three EKFs in parallel and combining the filtered states using an interacting multiple model (IMM) [4] automatically assigns probabilities to each mode, based on their likelihood of being correct. Here we use these IMM mode probabilities to visualize the dusty plasma kinematics.

II. RESULTS

TRACKING 3000 particles is intractable using a single EKF-based dynamic state estimator [7]. Here we have used 3000 independent trackers, each tracking a single particle. There are a number of selectable parameters involved in designing an extended Kalman filter, and an interacting multiple model tracker. In addition to careful mode design and noise-level selection, important design parameters for the IMM are the mode-transition probabilities, \( p_{ij} \). These should reflect the actual system’s mean sojourn times for each mode [4]. Here we have used

\[
\begin{pmatrix}
0.70 & 0.05 & 0.25 \\
0.05 & 0.70 & 0.25 \\
0.05 & 0.05 & 0.90
\end{pmatrix},
\]

(1)

reflecting the fact that we expect the particles to spend less time in modes 1 (“presence”) and 2 (“aftermath”), than in mode 3 (“absence”). The shockwave progression through the dusty plasma can be visualized via color-coded mode-probabilities, as shown in Figure 1. The red/blue/green intensity is determined by the probability for mode 1/2/3. The shock wave formation is clearly visible as a red region in the lower-left corner, with clearly visible shock-front propagation through space and time towards the upper-right corner. Along the way, the shock front splits in two. Post-shock-wave reflection of dust particles off the dust cloud bulk is visible as the faint blue region in the upper-left corner of Figure 1.

Figure 1 shows that the IMM mode probabilities are useful for visualizing the dust kinematics in a dusty plasma. Beyond visualization, specific physics about the dust can be extracted by an EKF-IMM tracker. Examples include kinetic temperature (from particle velocities), particle-number density (from particle positions). Indeed, any quantity related to the particle kinematics can be estimated in this manner. Importantly, in related work [7], we have found that a well-designed EKF-IMM tracker estimates the dust kinematics more accurately than particle tracking velocimetry (measurements alone). A future goal is to perform such dynamic estimation in real time,
Fig. 1. Color-coded image of IMM mode probabilities for X-position (horizontal axis) over time (vertical axis). The red/green/blue value for each pixel corresponds, respectively, to the mode probability in the presence/absence/aftermath of the shock wave. Propagation of the red shock front through the dust cloud is clearly visible, including bifurcation after $t = 0.3$s. The feint blue upper-left corner shows post-shock-wave reflection of particles off the dust cloud.

which would enhance the prospects for real-time control of a monolayer dusty plasma experiment.

III. CONCLUSION

Visualizing the kinematics of a monolayer of dust particles suspended in a plasma is not limited to using direct images of the dusty plasma. We have used an advanced dynamic-state estimation technique to track the kinetics of the dust particles (position/velocity/acceleration over time). Using a three-mode interacting multiple model state estimator based on an extended Kalman filter, we have produced particle-state estimates and associated mode probabilities. The mode probabilities reflecting the likelihood of each mode being a correct description of the dust particle dynamics. With a mode each designed for the presence, absence, and aftermath of a shock wave, we have visualized the dust kinematics (position vs. time) by mapping the three mode probabilities to the red, green and blue color intensities in Figure 1.

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