Smart dust: Monte Carlo simulation of self-organised transport

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Smart dust has been conceived as millimeter scale autonomous systems that form the basis for massively distributed wireless sensor networks[1, 2]. Smart dust motes have been demonstrated that pack sensors, interfaces, power sources, digital control communications and processing circuitry into a few cubic millimeters volume. Previously, both the delivery of a mote swarm and communicating with such systems has been studied. Here we address the problem of how to subsequently move dust motes around in their application environment. Solutions involving robot insect motes have been advocated where distances and times are small; but this introduces additional mechanical and electronic complexity plus severe constraints on power sources. Instead, we focus on the possibility of extracting power from the natural fluctuating forces that act on the motes. As an example, we consider the collective movement of motes towards a target S located in a portion of the Martian surface that extends over a range of several kilometers. This problem is part of a study for the design and fabrication of smart dust for future space exploration missions. A smart dust mote has approximately the density and volume of a coarse grain of sand. It follows that the uncontrolled motion of smart dust is determined by the same Aeolian processes of saltation, settling and surface creep that govern the movement of sand in desert regions [3]. For example, saltation involves the random lofting of a grain into the ambient wind flow where it becomes entrained, later falling to ground: whereupon the process repeats. Sand (and by implication smart dust) may also become electrically charged in a Martian environment [4]. The simulation of this problem has features that correspond to classical studies of electron transport/trapping in semiconductor devices near rough interfaces. We use Monte Carlo simulation of the mote dynamics coupled to a wind profile computed from the Navier-Stokes equations: for fixed drag coefficients the results are standard. Here we present the resulting 2D and 3D transport for smart dust motes that alter their drag coefficients, for example, by a shape change, when a favourable entrainment to the turbulent wind moves the motes towards the target. The induced correlation of the motion with the target relies on inertial effects (transient response) and exploits time-dependent fluctuations in the wind pattern. At low Reynolds numbers (which would apply to NEMS motes of sizes in the 10 micron range acting in a small region) the motion corresponds to adaptive diffusion or adaptive Brownian motion. At the high Reynolds numbers considered here, the wind flow is turbulent with speeds of the order of 3 – 20 m s^{-1}. The results indicate that switchable drag coefficients provide a mechanism for self-control of mote motion. The use of sensory information produces self-organising or anti-thermodynamic behaviour. Collective effects are possible, for example, if the target S represents the centre of mass of the swarm. The latter may be sensed from the mean signal received periodically from the host swarm. In our experimental programme the mote surface profile is altered by using low-power electrical stimulation of an outer electro-active polymer layer.

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A full journal publication of this work will be published in the Journal of Computational Electronics.

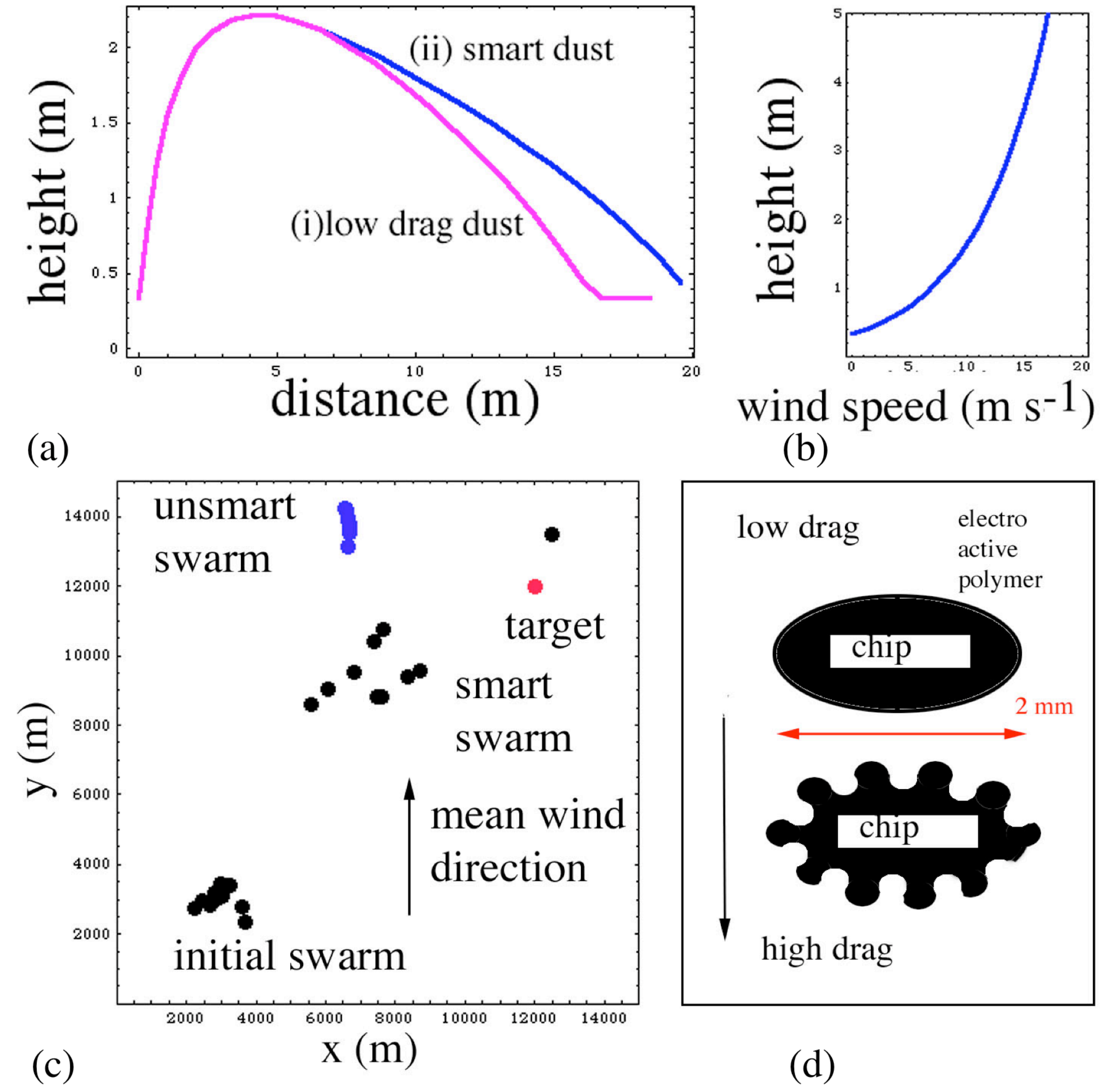

Figure 1: (a) (i) Trajectories computed: (i) for saltating low drag dust mote in stationary wind flow; (ii) for saltating smart dust mote- switches from low drag to high drag (factor 2) at peak of trajectory if velocity aligned with target. Achieves increased reach towards target. Large changes require significant drag changes.(b) Horizontal wind profile for case (a) computed from Bagnold equation [1] for Mars data. Critical wind speed to entrain motes depends on mote geometry and dimensions. (c) Small swarm movement in high speed turbulent wind across large area: (i) unsmart dust motes; (ii) smart dust motes. Average horizontal wind velocity to the North at 3 m s^{-1}. Wind flow is turbulent and non-stationary. Computation shows initial and final states computed by Monte Carlo simulation for smart and unsmart dust. The smart dust changes drag coefficient when direction to target is favourable. (d) Schematics of shape changing via stimulation of electroactive polymer sheath to alter drag .

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