Proof-of-Concept Swarm of Self-Organising Drones Aimed at Fighting Wildfires

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I. INTRODUCTION

Swarm Intelligence (SI) comprises a relatively novel route to Artificial Intelligence (AI) which stems from decentralised and self-organising behaviour observed in groups of simple social animals in nature such as ant and bee colonies, fish schools, and bird flocks. By way of collaboration, these animals are able to accomplish tasks that are far beyond their individual capabilities, and even beyond the simple aggregation of all of their individual capabilities. That is to say, the whole is more than the sum of its parts. Thus, SI is the branch of AI that deals with the collective behaviour that emerges from decentralised self-organising systems. Self-Organisation occurs with no central control or sense of purpose, as individuals only interact locally with one another and with the environment, inducing the emergence of coherent global patterns. Swarm robotics is a novel approach to the coordination of large numbers of simple and relatively inexpensive robots, which emerged as the application of SI to multi-robot systems. Different from other SI studies, swarm robotics puts emphasis on the physical embodiment of individuals [1].

Swarm robotics and Unmanned Aerial Vehicles (UAVs) technology have progressed at an increasingly fast pace for the past two decades, extending their capabilities and the kinds of problems they can help tackle. UAVs can now be equipped with a range of advanced cameras, thermal imagers and sensors which enable them to operate in remote areas, dangerous environments, and even through solid smoke while still being able to perform tasks such as surveying, mapping or locating people. Some of their current applications include aerial photography and filming, information gathering, provision of essential supplies for disaster management, support of search and rescue operations, mapping inaccessible locations, field surveying, and crop health monitoring. Autonomous UAVs have been used to establish resilient communications networks for emergency response [2] [3]. With regards to fire-fighting, UAV technology has been used to perform tasks such as forest surveillance, building fire risk maps, wildfire detection and monitoring, gathering data for a human decision-maker, assisting search and rescue operations, and situational awareness [4].

Given the hazardous nature of the activity, fighting fires by means of disposable and relatively inexpensive robots in place of humans is of special interest. In addition, the use of fleets of decentralised cooperative and self-organising robots results in a robust and resilient system with distributed decision-making which can cope with uncertainty, errors, and the failure or loss of a few nonessential units without jeopardising the overall mission. However, to the best of our knowledge, the use of self-organising swarms of autonomous UAVs for the actual deed of putting out fires has remained notably unexplored.

This paper comprises a proof-of-concept to demonstrate the feasibility and potential of employing swarm robotics to fight fires autonomously. To this end, an efficient yet realistic physics-based model of the spread of wildfires is developed, which is then coupled with a model of a fleet of self-organising drones whose coordination mechanism is based on a forgetful particle swarm algorithm. The aim is to develop algorithms for swarms of autonomous drones to self-organise to develop the ability to fight the spread of wildfires without human intervention. This research is timely, since Robotics and AI (RAI) as well as Robotics and Autonomous Systems (RAS) are identified as priority areas by the Engineering and Physical Sciences Research Council (EPSRC), as well as in the Industrial and Digital Strategies [5], [6] [7]. In addition, the UK government identified RAS as one of the Eight Great Technologies that will propel the UK to future growth [8], [9]. This topic is also supported by the UK-RAS Network which predicts that RAS will play an increasingly important role in disaster relief by reducing costs and response times and increasing capabilities [10].

II. FIRE-SPREAD MODEL

A physics-based fire-spread model was designed and implemented as a two-dimensional reaction-diffusion equation that describes the combustion of a mono-phase medium composed of pre-mixed gas of fuel and air.

This comprises a simplified version of the model in [11]. It is also assumed that there is no atmospheric wind and the transport equations can therefore be neglected.
In order to compensate for this, the diffusion coefficient is increased and two pseudo-3D terms are added into the energy balance equation to account for the energy losses due to convection and radiation in the third dimension.

Radiation in the horizontal directions is modelled to affect only the neighbour cells. The heat capacity at constant pressure is assumed to be constant for each chemical species within the considered temperature range. The fire-spread model can be represented by a system of five partial differential equations, one for the enthalpy balance and four for the chemical species formation (CO_2 and H_2O) or consumption (Fuel and O_2):

$$\begin{cases} \rho c_p \dfrac{\partial T}{\partial t} = -\rho h_c \dfrac{M}{M_{fuel}} r + k\dfrac{\partial}{\partial x}\left(\dfrac{1}{c_p}\dfrac{\partial c_p T}{\partial x}\right) + k\dfrac{\partial}{\partial y}\left(\dfrac{1}{c_p}\dfrac{\partial c_p T}{\partial y}\right) + \dots \\ + k\dfrac{\partial}{\partial x}\left(\dfrac{1}{c_p}\dfrac{\partial h_c}{\partial x}\right) + k\dfrac{\partial}{\partial y}\left(\dfrac{1}{c_p}\dfrac{\partial h_c}{\partial y}\right) + C_a(T_0 - T) + \sigma\varepsilon\left[4dx\dfrac{\partial}{\partial x}\left(T^3\dfrac{\partial T}{\partial x}\right) + 4dy\dfrac{\partial}{\partial y}\left(T^3\dfrac{\partial T}{\partial y}\right) + \dfrac{T_0^{\,4} - T^4}{dz}\right] \\ \dfrac{\partial X_\alpha}{\partial t} = -\dfrac{\theta_\alpha}{\theta_{fuel}} \cdot \dfrac{M}{M_{fuel}} \cdot r \quad \text{with} \quad \alpha = 1,\dots,4 \end{cases} \tag{1}$$

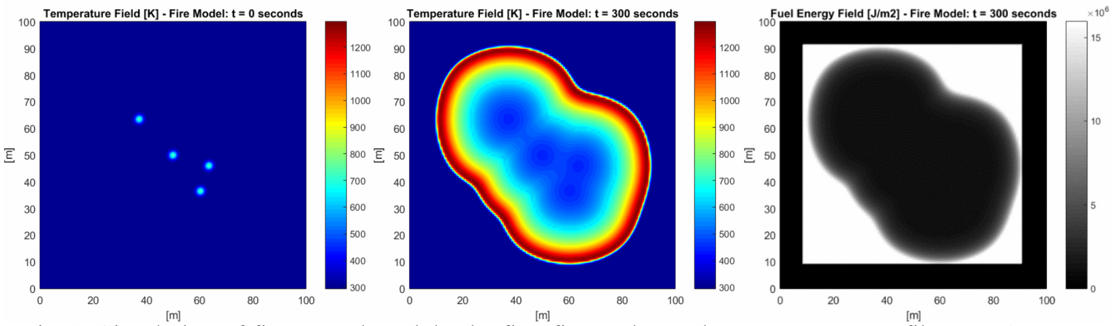

Fig. 1: Simulation of fire-spread model. The first figure shows the temperature profile once 4 sparks have occurred, the second one shows the temperature profile after 5 minutes, and the last one shows fuel energy density after 5 minutes (black: no fuel).

The system is closed with the equations for the molar mass of the mixture, the heat capacity of the mixture, the combustion rate (Arrhenius equation), and the combustion enthalpy. Fig. 1 shows an example of this model being used for the prediction of the temperature profile and fuel energy density five minutes after four sparks have occurred. While very efficient, the simulation of this model using Matlab and a standard PC still runs about five times slower than real-time (without visualisation).

III. SELF-ORGANISATION MODEL

At this early stage of the research, the swarm of drones has been modelled as 2D massless particles whose self-organisation is based on the particle swarm algorithm. Modifications were introduced to handle particles' memories in a dynamic environment, and to

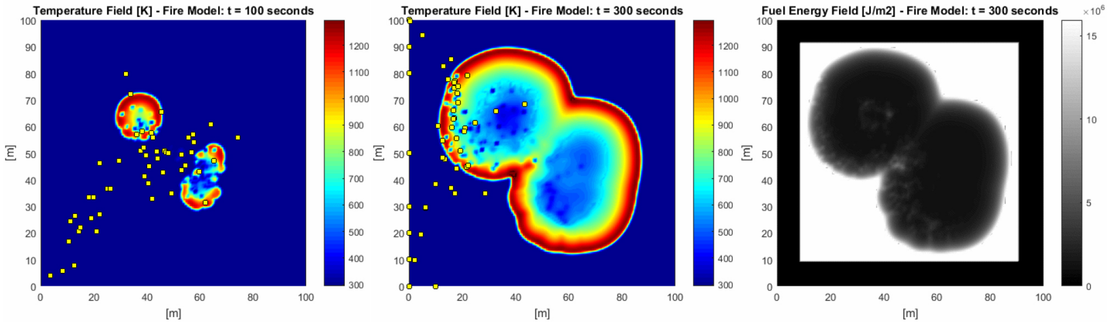

Fig. 2: Simulation of self-organising drones fighting the spread of a wildfire. The first figure shows temperature 100 seconds after 4 sparks have occurred, the second one shows the same after 5 minutes, and the last one shows fuel energy density after 5 minutes.

control the level of stochasticity so as to smoothen the erratic behavior. While the fire model is updated every quarter of a second, sensor measurements and drones' memories are updated every second. Maximum speed permitted is set to 10 m/s.

I.V. FUTURE WORK

Future work includes the incorporation of collision avoidance algorithms, and the modelling of the actual drones to include flight dynamics and local controllers. We have also developed a more advanced fire- spread model which accounts for transport phenomena due to varying pressure and temperature inspired by [12] and [13], though atmospheric wind is yet to be included.

However, this model is too demanding to be used extensively. We are also exploring the use of the Fire Dynamics Simulator (FDS) [14], the FIRESITE wildfire growth simulator [15], and of models based on cellular automata and Lattice Boltzmann.

REFERENCES

1. Şahin, S. Girgin, L. Bayindir and A. E. Turgut, "Swarm Robotics," in *Swarm Intelligence. Natural*
2. *Computing Series*, C. Blum and D. Merkle, Eds., Springer, Berlin, Heidelberg, 2008, pp. 87-100.
3. S. Hauert, S. Leven, J.-C. Zufferey and D. Floreano, "The swarming micro air vehicle network (SMAVNET) project," [Online]. Available: http://lis2.epfl.ch/CompletedResearchProjects/SwarmingMAVs/index.php. [Accessed 12 01 2018].
4. J. Ueyama, H. Freitas, B. S. Faiçal, G. P. Filho, P. Fini, G. Pessin, P. H. Gomes and L. A. Villas, "Exploiting the use of unmanned aerial vehicles to provide resilience in wireless sensor networks," *IEEE Communications Magazine,* pp. 81-87, 2014.
5. J. C. Jones, "SMART fire fighting: the use of unmanned aircraft systems in the fire service," *NFPA 2015 Responder Forum,* 2015.
6. "Building our Industrial Strategy," HM government green paper, 2017.
7. "Industrial strategy. Building a Britain fit for the future," HM government white paper, 2017.
8. "The Digital Strategy," HM government policy paper, 2017
9. Willets, "Eight Great Technologies," Policy Exchange, London, 2013.
10. "Robotics and Artificial Intelligence, Fifth Report of Session 2016-17," House of Commons Science and Technology Committee, 2016.
11. "Extreme Environments Robotics: Robotics for Emergency Response, Disaster Relief and Resilience," UK-RAS white papers, 2017.
12. L. Ferragut, M. I. Asensio and S. Monedero, "A numerical method for solving convection–reaction– diffusion multivalued equations in fire spread modelling," *Advances in Engineering Software,* vol. 38, pp. 366-371, 2007.
13. Séro-Guillaume and J. Margerit, "Modelling forest fires. Part I: a complete set of equations derived by extended irreversible

thermodynamics," *International Journal of Heat and Mass Transfer,* vol. 45, pp. 1705-1722, 2002.
14. J. Margerit and O. Séro-Guillaume, "Modelling forest fires. Part II: reduction to two-dimensional models and simulation of propagation," *International Journal of Heat and Mass Transfer,* vol. 45, p. 1723–1737, 2002.
15. K. McGrattan, S. Hostikka, R. McDermott, J. Floyd, C. Weinschenk and K. Overholt, "Fire Dynamics Simulator Technical Reference Guide. Volume 1: Mathematical Model," VTT Technical Research Centre of Finland, 2013.
16. A. Finney, "FARSITE: Fire area simulator-model development and evaluation," U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 2004.