A Hybrid-System Formalism to Verify Properties of Robot Swarms

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1 Abstract

Robot swarms constitute an attractive solution to carry out tasks where the environment may pose a threat to human operators or where single robots would not be able to perform efficiently. Their robustness and scalability arise from a fully decentralised control architecture and make them preferable in such scenarios to multi-robot systems controlled in a centralised fashion. While interest in this field has been growing steadily over the past twenty years, a systematic method to design the control software for each of the individual robots in a way that guarantees some desired properties of the resulting collective behaviour is still missing. This is one of the main limitations that hinders the use of robot swarms in real-world applications. In this project, we aim to develop a framework that allows to describe the desired properties of a swarm and automatically generate control software that ensures such properties.

Robot swarms consist of relatively simple robots (see Figure 1), which frequently interact with each other in their pursuit of a common goal. Together with the systematic uncertainties introduced by imperfect sensors and actuators, this makes the resulting system behaviour highly unpredictable. A common approach to the verification problem has been to model robot swarms as Markov chains and use model-checking tools. We argue that the use of hybrid systems to model robot swarms allows for a desirable abstraction of the swarm dynamics and may therefore be used to formally verify a richer variety of their properties. For previous work that followed the same motivation, see [1].

In our approach, we define the properties of a robot swarm as constraints on appropriate state variables, such as inter-robot distances and velocities. Such properties reflect characteristics of the swarm behaviour that may be required or desired for a given task, such as collision avoidance or aggregation at a given location. A review of swarm robotics tasks can be found in [2]. This approach, while more common in the field of control theory than in swarm robotics, allows us to systematically produce inequality constraints that are platform-agnostic and, thus, generalisable.

Figure 1: The e-puck robot, a swarm robotics platform of widespread use for research purposes.

Through these constraints, we define differential invariants, which may be used to either complement bounded model checking tools or for deductive verification. In particular, we explore the use of differential dynamic logic (d$\mathscr{L}$), which follows the grammar

$$\begin{aligned}\phi,\psi ::= &p(\theta_1,\dots,\theta_n)|\neg\phi|\phi\wedge\psi|\phi\vee\psi|\phi\rightarrow\psi|\\ &\forall x\psi|\exists x\psi|[\alpha]\phi|\langle\alpha\rangle,\end{aligned} \tag{1}$$

where ϕ and ψ are formulas, θ_1 and θ_2 are terms, p is a predicate symbol, x is a logical variable and α is a hybrid program [3]. Extensions of d$\mathscr{L}$, including differential dynamic temporal logic (dTL) and quantified differential dynamic logic (Qd$\mathscr{L}$), provide tools for reasoning about the temporal behaviour of hybrid systems and about distributed hybrid systems, respectively.

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