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# A class of intelligent agents for coordinated control of outdoor terrain mapping UGVs

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**Abstract**

This article develops a systems- and control-oriented intelligent agent framework called the hybrid intelligent control agent (HICA) and describes its composition into multiagent systems. It is essentially developed around a hybrid control system core so that knowledge-based planning and coordination can be integrated with verified hybrid control primitives to achieve the coordinated control of multiple multi-mode dynamical systems. The scheme is applied to the control of a team of unmanned ground vehicles (UGVs) engaged in an outdoor terrain mapping task. Results are demonstrated experimentally.


*Keywords:* Autonomous agents; Terrain mapping; Hybrid systems; Intelligent control

## 1. Introduction

One challenge that faces the intelligent systems and control communities is how to respond to the increasing demand for more intelligent higher autonomy systems-of-systems. These range from combat applications which require teams of coordinated autonomous unmanned air and ground vehicles (UAVs and UGVs) to complex interconnected electric power systems made up of several interacting entities. For the autonomous vehicles scenario, each team member (e.g., small unmanned rotorcrafts and certain ducted fan vehicles) may exhibit both continuous-valued and discrete-event dynamic behaviour (i.e., a hybrid system). The challenge is to synthesize low-level control schemes for the various modes of the vehicles which interact seamlessly with higher-level logic mechanism used to coordinate and/or supervise such a vehicle team. Owing to their inherent complexity, problems like these have been decomposed and modelled as systems of multiple interacting *intelligent agents* (Wooldridge, 1999; Jennings et al., 1998; Weiss, 1999; Georgeff and Rao, 1998).

For the purposes of this article, we define an agent as a system/process which is capable of sensing, computing and acting within an environment it occupies so that its actions are carried out in a flexible autonomous manner to optimize the attainment of its objectives and to affect its surroundings in a desired manner. Three broad classes of agents are identifiable (more specific classifications may be found in Russell and Norvig (1995)). In a *reactive* agent, perception is tightly coupled to action without the use of any symbolic or abstract internal model of the agent, the environment or their time

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histories. A *deliberative* agent system reasons and acts based on an internal model of both itself and the environment it inhabits. *Hybrid* agent systems combine aspects of both reactive and deliberative agency. The HICA belongs to this last category.

The field of multi-agent systems (MAS) is a vibrant part of distributed artificial intelligence with the broad aim of laying down the principles for the construction of complex systems involving multiple agents and providing tools/mechanisms for coordination of independent agent behaviours. A MAS environment is intended to interconnect separately developed agents so that the ensemble performs better than any one of its members. They also make it possible for the problem of constraint satisfaction to be sub-contracted to different problem-solving agents each with its own capabilities and goals. This MAS paradigm provides structures for building systems with high autonomy and for specifying interaction and coordination rules among agents. The core objective is the solution of problems too large for just one centralized agent to deal with, for instance control and/or resource allocation problems in distributed systems like air traffic control (Georgeff and Rao, 1998), telecommunication networks (Hayzelden and Bigham, 1998), industrial process control (Velasco et al., 1996) and electric power distribution (Wittig, 1992). Specific instances of successful practical application of MAS in these and other areas are summarized in the excellent work by Parunak (1999). The concept of agents situated in an environment is adapted from that work and shown in Fig. 1.

While the subfield of multiagent systems has a great deal to offer in terms of encoding flexible intelligent behaviour and coordination, its solutions are not easily represented or analyzed mathematically. By the same token, while there are many elegant mathematical results from decentralized control theory (Šiljak, 1996), systems based on these tend to be brittle and have primitive coordination abilities. Additionally, the class of systems to which much of the theory applies is still restricted.

For systems and control applications, it is important that there be transparent means of embedding control laws in an agent and for analyzing the resulting system behaviour. Since autonomy is central to the notion of agents, it is equally important to develop schemes which allow flexible coordination among agents. Accordingly, the key premise of this work is that future high autonomy systems-of-systems in which each system exhibits hybrid behaviour require *both provably stable control schemes (obtainable by applying control theoretic tools) and intelligent supervision and coordination abilities (developed by using tools from the subdiscipline of multiagent systems)*. We submit that such an agent framework that lends itself to mathematical representation/analysis requires a modification to the basic agent paradigm to make its dynamics accessible. In the modified agent framework, a hybrid control system is embedded in the core of the agent. Essentially, the abstract 'agent state' in Fig. 1 is replaced by a hybrid automaton and an associated controller. This makes it possible to transparently represent systems with multiple modes and to design suitable control laws that are valid for these modes. It also provides a more intuitive scheme to design for achieving specific control objectives for systems with multiple modes without sacrificing the intelligence and coordination inherent in the 'agent process' of Fig. 1. Additionally, mathematical tools from the theory of discrete event systems, hybrid systems and automata theory become applicable for the description of systems based on such enhanced agents.

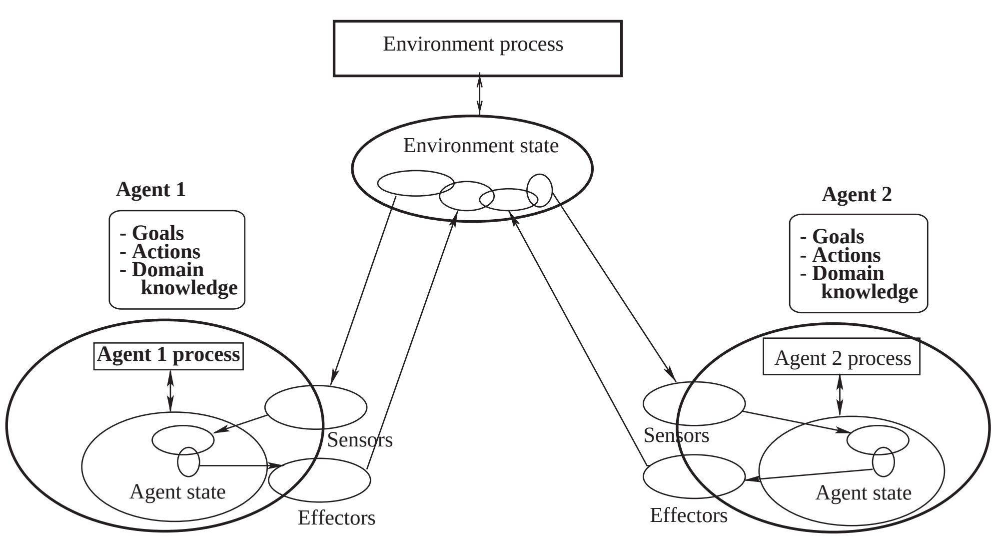


Fig. 1. Agents in an environment.