

Distributed Intelligent Control Theory of Hybrid Systems

Xiaolin Ge, Anil Nerode, Wolf Kohn, John James

Abstract: We discuss recent advances in multiple-agent, distributed control of interactive processes. Our multiple agent hybrid control architecture approach is a new technology with broad applicability since it integrates the application of logic (set-based) and continuous-time models of complex system behavior. The Kohn-Nerode approach for integration of hybrid systems emphasizes *on-line synthesis* of automata which will meet *current* constraints. A key feature of the approach is that the evolution of the behavior trajectory of the automata (e.g. the behavior trajectory of agent *i*) is continuous in the carrier manifold (explained below). We provide an example of our results by discussing the case of multiple agents involved in the engagement of multiple targets, the agent behavior is continuous with respect to the multiple engagement process models whose

potentials determine the portion of time the process is active in a time interval.

1. A New Concept of System State

Hybrid System State: For purposes of our exposition, there are three cases which need to be considered in the characterization of unified information models represented in the computer. These cases collectively contain the kinds of information that describe the *state of the system*. The cases are: (1) information derived from monitoring continuous variables, (2) information derived from monitoring variables which normally evolve continuously but which may exhibit logical changes (jumps), and (3) information which is derived from logical variables (See Figure 1).

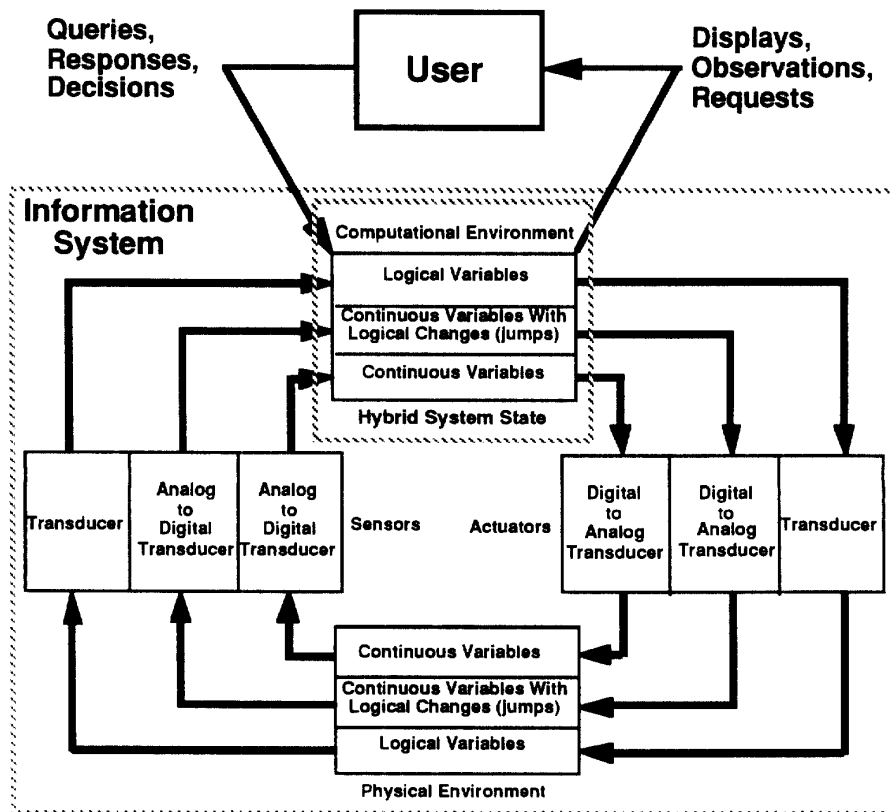


Figure 1. Hybrid System State Representation

To represent the state of the system in a computable model, the values of continuous variables must be approximated, as must the values of variables which are normally continuous but may occasionally exhibit jumps. This is achieved by A-D and D-A transducers. Exact representation of logical variables can be achieved using transducers. The data structure of the hybrid system state in the computational environment is a composition of logical and evolution variables. The state of the system in the physical environment is approximated by the state of the system in the computational environment (the hybrid system state). The information system of the user includes direct observation of the physical system as well as information available from the user interface of the computational environment. The hybrid system state evolves over time as the physical environment is altered by the user (s) and by the actuators of the system.

The current technical approach for construction of computational models for sending signals to actuators is based on experimentally integrating logical and evolution models of the physical environment. The *inefficiency* in requiring experimental verification and validation that the

safety, security, and functional system requirements are satisfied is a *fundamental barrier* to lowering the costs of integrating existing complex information systems. Previous efforts to improve the integration process have been hampered by the fact that there has not been a mathematical framework for simultaneously analyzing safety, security, and other logical requirements while also considering temporal and spatial constraints. Our creation of the hybrid system state provides the technical foundation to achieve the *unification* of logical and evolution models. Our multiple-agent declarative control architecture provides the analytical framework to simultaneously comply with evolution and logical constraints.

Attainment and maintenance of a computable model is accomplished through analysis of the hybrid system state. The Kohn-Nerode approach for unification of logical and evolution models is based on introducing the idea of continuity of the hybrid state representation. The continuity argument and the constructive extraction of automata which comply with the continuity constraint is accomplished by using the mathematics of manifolds (see Figure 2). A

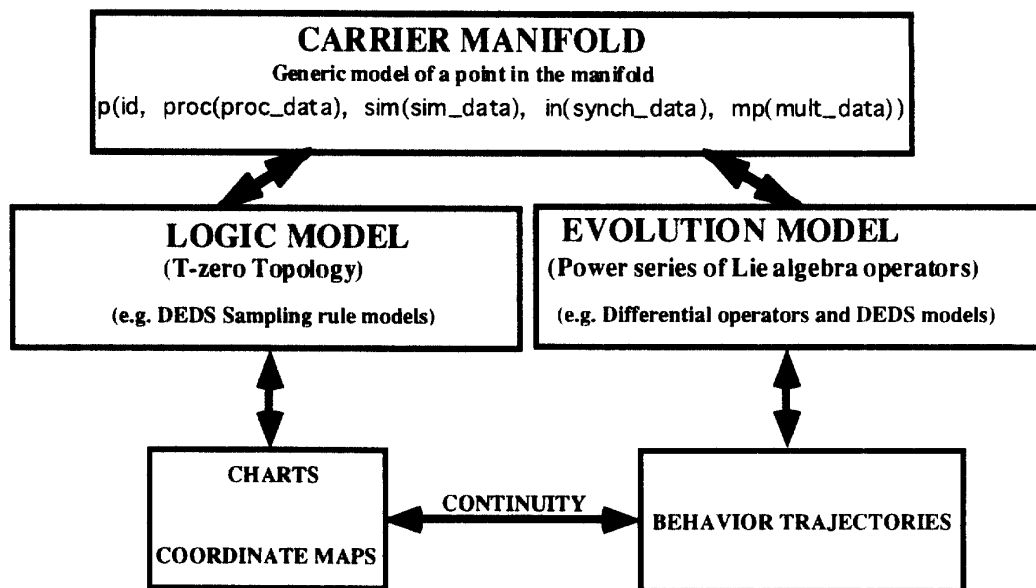


Figure 6. Generic model of a point in the carrier manifold

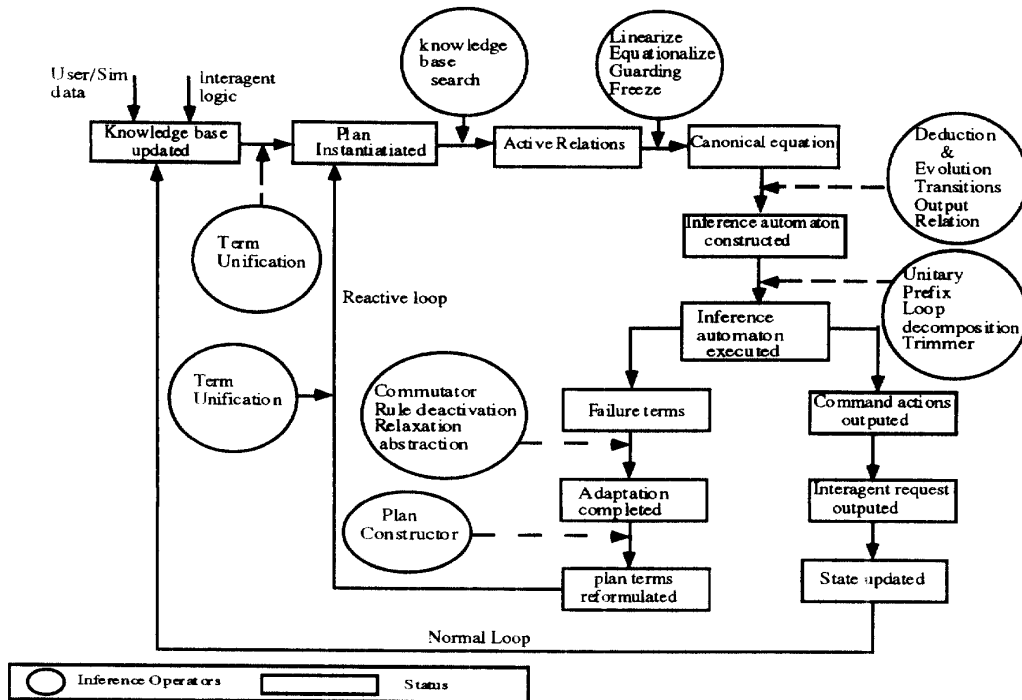


Figure 3. Data Flow Model of Points in the Carrier Manifold

point in a manifold supports unification of logic and evolution models. T-zero topologies have a one-to-one correspondence with horn clauses of logical representations. This enables us to model the Discrete-Event Dynamic System (DEDS) sampling rule models. Lie algebra results concerning infinitesimal operators on smooth functions allow us to consider all the standard evolution models of differential operators and DEDS evolution models. We embed logical models in continuous models in order to construct automata which comply with logical and continuum constraints. Details of the generic unified model are given separately. The data flow model of points in the carrier manifold is given in Figure 3. We assert and emphasize here that for systems which meet the conditions for creation of a hybrid system state, the revolutionary nature of our approach has two benefits:

- Creation of a unified mathematical foundation for analysis and synthesis of models which for decades have been treated separately, and
- Creation of a rigorous process for incremental expansion of trusted systems

which must comply with stringent safety and performance constraints.

2. A New Approach to Aggregation and Disaggregation of Components

Agent characteristics: Each agent of the declarative control architecture operates as a real-time theorem prover in the domain of relaxed variational theory developed by L. C. Young [13]. A *customized* version of this theory, enriched with elements of differential geometry and equational logic provides a general representation for the dynamics, constraints, requirements and logic of complex computer-controlled systems.

We will provide an overview of a generic hybrid system architecture and provide a domain reference architecture for target engagement. The agents are connected via an inter-agent network and the effect of each agent in the global network on a local agent is obtained through a global-to local transformation. Inter-agent specification clauses characterize constraints on the

relaxed Lagrangian optimization problem. Specifically, they express the constraints imposed by the rest of the network on each agent. They also characterize the global-to-local transformations and local-to-global transformations (see [45]). Finally, they provide the rules for building a generalized multiplier for incorporating the inter-agent constraints into a complete unconstrained criterion. The multiplier and transformations are expanded in rational power series in an algebra discussed in [46].

The conjunction of equational forms for each global-to-local transformation is constructed by applying the following invariant embedding principle:

"For each agent, the actions at given time t in the current interval are the same actions computed at t when the formulation is expanded to include the previous, current, and next intervals."

By transitivity and convexity of the criterion, the principle can be analytically extended to the entire horizon. The invariant embedding equation has the same structure as the dynamic programming equation given in, but with the global criterion and global Hamiltonians instead of the corresponding local ones.

The local-to-global transformations are obtained by inverting the global-to-local transformations, obtained by expressing the invariant embedding equation, as an equational theorem. These inverses exist because of convexity of the relaxed Lagrangian and rationality of the power series.

3. Conclusion: We have provided an overview of the theory of multiple-agent hybrid control. We are currently implementing a multiple-agent hybrid control architecture for the target engagement process.

[1] Nerode, A. and Kohn W." Multiple Agent Declarative Control Architecture" Proc. of the workshop on Hybrid Systems, Lygby, Denmark, Oct 19-21, 1992.

[2] Nerode, A. and Kohn W." Foundations Of Hybrid Systems" In Hybrid Systems, Nerode, A, R, Grossman Eds. Springer Verlag series In Computer Science #726, New York, 1993.

[3] Kohn W., and Nerode A., "Multiple-Agent Hybrid Systems" Proc. IEEE CDC 1992, vol 4, pp 2956, 2972.

[4] Kohn, W. "declarative Control Architecture" CACM Aug 1991, Vol34, No8.

[5] W Kohn, Nerode A. " An Autonomous Systems Control Theory: An Overview" Proc. IEEE CACSD'92, March 17-19, Napa, Ca., pp 200- 220.

[6] Kohn W., and Nerode A. "Models For Hybrid Systems: Automata, Topologies, Controllability, Observability" Technical Report 93-28, MSI, Cornell University, June, 1993.

[7] Garcia, H.E. and A. Ray "Nonlinear Reinforcement Schemes for Learning Automata" Proceedings of the 29th IEEE CDC Conference. Vol. 4, pp 2204-2207, Honolulu, HA, Dec. 5-7, 1990.

[8] Kohn W. and Nerode A. "multiple Agent Hybrid Control Architecture" MSI Report 93-11 Cornell U.

[9] Kohn, W. "Declarative Hierarchical Controllers" Proceedings of the Workshop on Software Tools for Distributed Intelligent Control Systems, pp 141-163, Pacifica, CA, July 17-19, 1990.

[10] Kohn, W. and T. Skillman "Hierarchical Control Systems for Autonomous Space Robots" Proceedings of AIAA Conference in Guidance, Navigation and Control, Vol. 1, pp 382-390, Minneapolis, MN, Aug. 15-18, 1988.

[11] Kohn, W. "A Declarative Theory for Rational Controllers" Proceedings of the 27th IEEE CDC, Vol. 1, pp 131-136, Dec. 7-9, 1988, Austin, TX.

[12] Kohn W. " Multiple Agent Inference in Equational Domains Via Infinitesimal Operators" Proc. Application Specific Symbolic Techniques in High Performance Computing Environment". The Fields Institute, Oct 17-20 1993.

[13] Young, L.C. "Optimal Control Theory" Chelsea Publishing Co., NY, 1980.

[14] Padawitz, P. "Computing in Horn Clause Theories" Springer Verlag, NY, 1988.

[15] Kohn W. "Multiple Agent Hybrid Control" Proc of the NASA-ARO Workshop on formal Models for Intelligent Control, MIT, sept 30-Oct2, 1993.