# INTERIM PROGRESS REPORT: INTELLIGENT CONTROL ARCHITECTURES FOR UNMANNED AIR VEHICLES

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S. S. Sastry, D. N. Godbole, J. Malik, R. Sengupta,
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Memorandum No. UCB/ERL M97/86

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# Interim Progress Report: Intelligent Control Architectures for Unmanned Air Vehicles

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This document is a report on the work conducted on ONR grant number N00014-97-1-0946 from July, 1, 1997 to date.

This project is concerned with the design and evaluation of Intelligent Control Architectures for Unmanned Air Vehicles. The three proposed research thrusts were

1. Intelligent Control Architecures for Coordinating UCAV's.

2. Verification and Design Tools for Intelligent Control Architectures.

3. Perception and Action Hierarchies for vision based control and navigation.

The first section restates the project concept. The next three sections describe our progress on the three research thrusts identified in our proposal. Section 5 summarises Sections (2),(3), and (4) with reference to the timelines and deliverables in our proposal. Appendix A is a set of viewgraphs that describe results to date pertaining to research thrusts 1 and 2 above.

## 1 Project Concept

Impressive advances in computation, communication, smart materials, and Micro-Electro-Mechanical Systems bring closer to realization, the promise of furthering the cybernetic dream of building autonomous intelligent systems. These are systems that sense and manipulate their environment by gathering multi-modal sensor data, compressing and representing it in symbolic form at various levels of granularity, and using the representations to reason and learn about how to optimally interact with the environment. The problem is hard because real-world environments are complex, spatially extended, dynamic, stochastic, and largely unknown; intelligent systems must also accommodate massive sensory and motor uncertainty and must act in real time. We believe that qualitative leaps in scope and performance will emerge from addressing the basic problems together. Complexity and spatial extent are addressed by system decomposition based on hierarchical, hybrid, and multi-agent designs, using multiple levels of abstraction for sensory and control functions. Structural and parametric learning methods adapt the system to initially unknown environments, while generalized estimation methods, uncertainty management, and robust control techniques cope with the residual uncertainty inherent in stochastic, partially observable environments. Real-time decision-making is achieved by parallelism, reflexive control, compilation, and anytime approximation algorithms. To a large extent, control theory, artificial intelligence, and computational neuroscience investigate the very important paradigm of Central Control. In this paradigm, sensory information is collected from sensors observing a material process that may be distributed over space. This information is transmitted over a communication network to one center, where the commands that guide the process are calculated and transmitted back to the process actuators that implement those commands. While this is eminently desirable for the optimization of system-wide mission objectives, the need to maintain the rapid response and high survivability associated with autonomous multi-agent operation, demands an architectural fusion of the central control paradigm with that of autonomous intelligent systems, i.e., a hierarchical perception and control paradigm for semi-autonomous intelligent systems. The following sections describe our progress on the three major research thrusts aimed at these problems.

## 2 Intelligent Control Architectures

We have begun a systematic investigation of the problem of designing intelligent control architectures for distributed systems. The successful completion of our investigations should result in an architectural design theory applicable to semi-autonomous multi-agent UCAV systems designed to execute coordinated surveillance or combat missions.

We view a control design problem as one that aims to design a safe and efficient control on the basis of a given observation structure. An architecture design problem is concerned with the design of both the observation and control. An architecture design problem for a distributed system begins with specified safety and efficiency objectives and aims to characterise communication, observation, and control. The conceptual separation between observation and communication is a distinction between local and remote observation in a spatially extended environment. One may think of the observation of an agent as the information derived from its sensors. In contrast, the communications received by an agent may be thought of as information derived from the sensing or control of another agent. This crucial separation of communication and observation in a distributed sytem is essential for architectural research.

We intend to investigate the intelligent control architecture design problem in three formalisms. They are the *intrinsic model* [14], *supervisory control of discrete event systems* [6] and the hybrid system formalism. In order to understand the purely combinatorial aspects of architecture design we have begun our investigation in the context of discrete event systems. By starting with this type of model we are able to take advantage of a literature characterising the relationship between distributed control and observation [8]. During the past few months we have developed insights into the communication requirements of intelligent distributed systems.

The hybrid system literature on multi-agent distributed control is small [15, 4]. Therefore parallely we have started to formulate the first distributed hybrid control problems. Fortunately, the research team has executed some distributed hybrid control designs for automated vehicle control and coordination problems [3]. This past experience together with research on vision guided navigation and control being done under this grant is proving to be invaluable in guiding our formulation of hybrid distributed control problems. With regard to the intrinsic model we have become aware that the ARO Low Power Communications MURI, led by the University of Michigan, is investigating distributed architecture design problems in this context [10]. We are collaborating our research with the group of Prof. Teneketzis in this area. One of our group (Sengupta) participated in a review of that center on November 13th, 1997.

Our investigations of discrete event models have yielded the following insights to date. We have formulated a multi-agent decentralized observation problem where each agent observes some events that occur in the system and environment and aims to detect the occurrence of a few distinguished events (see Appendix A). We think of these distinguished events as failure events. Therefore we state the problem as a decentralized diagnosis problem. In general, the observations of the agent are not rich enough to infer the events of interest and therefore the agents are connected by an inter-agent commmunication bus that they use to exchange messages. We have a result that characterises decentralized observation problems that cannot be solved by communication. For problems that can be solved we can algorithmically synthesize a communication scheme from a system model without communication. Unfortunately, the communication scheme we synthesize is inefficient in obvious ways. We believe that stronger results can be derived. Furthermore, we have realized that communication synthesis problems cannot be formulated within control synthesis frameworks formulated in the existing DES literature. A new modeling paradigm is required even within the DES context. On completion of our investigation of distributed observation and communication we intend to establish the connections with distributed control.

# 3 Design and Verification Tools

In our research on this project we are developing a new approach to probabilistic verification. The heart of the approach is to not verify that every run of the hybrid system satisfies certain safety or liveness parameters, rather to check that the properties are satisfied with a certain probability, given uncertainties of actuation and sensing. In this sense, this is a "softening" of the notion of verification and represents a rapproachment between stochastic control, Bayesian decision networks and soft computing. We are hopeful that this new softer approach to verification will push the decidability barriers that cloud in deterministic hybrid verification problems.

We are working on developing connections between the distributed architecture synthesis problems that we are investigating and the model-checking methods used in computer science. This rapproachment will enable the application of a large and sophisticated body of model-checking algorithms to architecture design. In the decentralized discrete event observation problem we are trying to state the decidability question as a CTL model-checking problem. There is already significant progress on formalizing the relationship between hybrid model-checking and centralized hybrid control design in research sponsored by the ARO MURI on Intelligent Hybrid Systems [11]. We hope to leverage some of this work in our investigation of distributed hybrid systems.

# 4 Perception and Action Hierarchies for Vision based control and navigation.

We are designing a perception and action hierarchy centered around the vision sensor to support the observation and control functions of air vehicles.

We have started developing a 3D virtual environment simulation that is a visualization tool for hierarchical vision processing and vision-centered control algorithms. The simulation and visualization environment will include vision algorithms for tasks such as object recognition, orientation and navigation. We are incorporating algorithms developed by PATH researchers for the vision guided navigation and control of automated vehicles and helicopter navigation and control algorithms developed for an experimental test bed aerial robotic helicopter. This comprehensive environment will enable this project to design and simulate new vision-centered navigation and control algorithms that build upon the legacy bequeathed by past projects.

The tool animates the air vehicle and creates an animation of the camera's view of the virtual environment. Algorithms developed for the vision tasks will be implemented and simulated on the sample image sequences produced by the camera's view. The vision system will perform tasks such as obstacle detection based on these image sequences and send new reference inputs to the controller to change the vehicle trajectory. In this way, the vehicle will perform high level tasks such as obstacle avoidance based on visual servoing. An on-board computer vision system provides artificial autonomous agents with the ability to perceive information about the environment they inhabit, and sense their ego-motion relative to the environment. For the unmanned autonomous air vehicle, vision will be used mainly for three purposes: *autonomous navigation, object recognition and manipulation (in rescue operations).*

experience gained from a comprehensive vision based navigation system for cars on an Intelligent Vehicle Highway System (IVHS) is useful in our current work on its appliaction to aerial vehicles. Recent developments in the computer vision theory on motion estimation and visual servoing [2, 5, 9, 12] provide new theoretical support for improving existing vision based navigation systems. These new results also open up a wide range of possibilities for combining vision with other inertial navigation sensors (for example, the gyroscope, accelerometer and GPS) to build hierarchical and hybrid sensing systems for autonomous air vehicles. Such sensing systems maintain features of higher accuracy and reliability.

Object recognition improves the intelligence of the autonomous vehicle in understanding its environment. In autonomous landing, the on-board vision system will help the vehicle to localize and track the landing mark, and, in a collaborative task with other vehicles, recognize partners. Another principal usage of vision will be to provide feedback information of manipulating on-board actuators (e.g., grasper, probe) to fulfill various tasks. Recent research on multi-body motion estimation from vision makes this approach even more appealing [1, 7, 13].

# 5 Summary

Our progress with respect to the proposed schedule and deliverables (see table) is satisfactory. We have started work in all three areas and have obtained preliminary results as described in sections 2, 3. and 4. Appendix A has viewgraphs explaining work done under the first two research areas. A working paper based on this work is in preparation. Other publications are also in the planning stage.

The deliverables listed in the table are classified as WP (for working papers), or SW (software design tools), or EXP (for experiments).

| Task | Symbol | Duration | Deliverables |
|---|---|---|---|
| **Intelligent Control Architectures** | | | |
| Specification Tools | **IC1** | 7/97 - 7/98 | WP, SW |
| Design Tools | **IC2** | 7/97 - 9/99 | WP, SW |
| Architecture Evaluation Environment | **IC3** | 7/97 - 7/00 | WP, SW |
| UCAV Application | **IC4** | 7/97 - 7/00 | WP, EXP |
| **Verification Tools** | | | |
| Design Mode Verification | **V1** | 7/97 - 12/98 | WP, SW |
| Faulted Mode Verification | **V2** | 7/97 - 9/99 | WP, SW |
| Probabilistic Verification | **V3** | 9/96 - 9/99 | WP |
| **Perception** | | | |
| Surveillance | **PH1** | 7/97 - 9/99 | SW, EXP |
| Hierarchical Vision | **PH2** | 7/97 - 7/00 | WP, SW |
| Visual Servoing | **PH3** | 9/97 - 7/00 | WP, EXP |
| UCAV Application | **PH3** | 7/97 - 7/00 | WP, EXP |

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# Appendix A: Fault Management in Complex Systems

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## *1.1 Complex Systems*

**Complex systems may have:**

- *multiple agents*
- *distributed, asynchronous sensing and control*
- *agents that are internally embedded real-time systems*
- *agents with individual safety and performance objectives*
- *global system objectives.*

**Normal or Fault mode design problems are highly complex.**

**Manage design complexity by creating an** *architecture*

- *hierarchically structured observation and control*
- *structured peer entity control coordination*
- *structured peer entity observation coordination*
- *designated coordinator agents for specific modes*

**Faults: Interested in hardware faults, i.e., faults are** *persistent.*

## *2.1 Outline*

- **A fault management architecture**
- **A formalism for top-level specification of the fault management control (Degraded Mode Control) and observation (diagnostic) problem**
- **Diagnostic problems in distributed, multi-agent systems**
  **- Centralized, Partially Decentralized, Fully Decentralized**
- **Fault Management in Intelligent Vehicle Platoons**
  **- Hierarchical distributed degraded mode design and verification**
  (*Godbole et.al., Towards a Fault Tolerant AHS Design*)

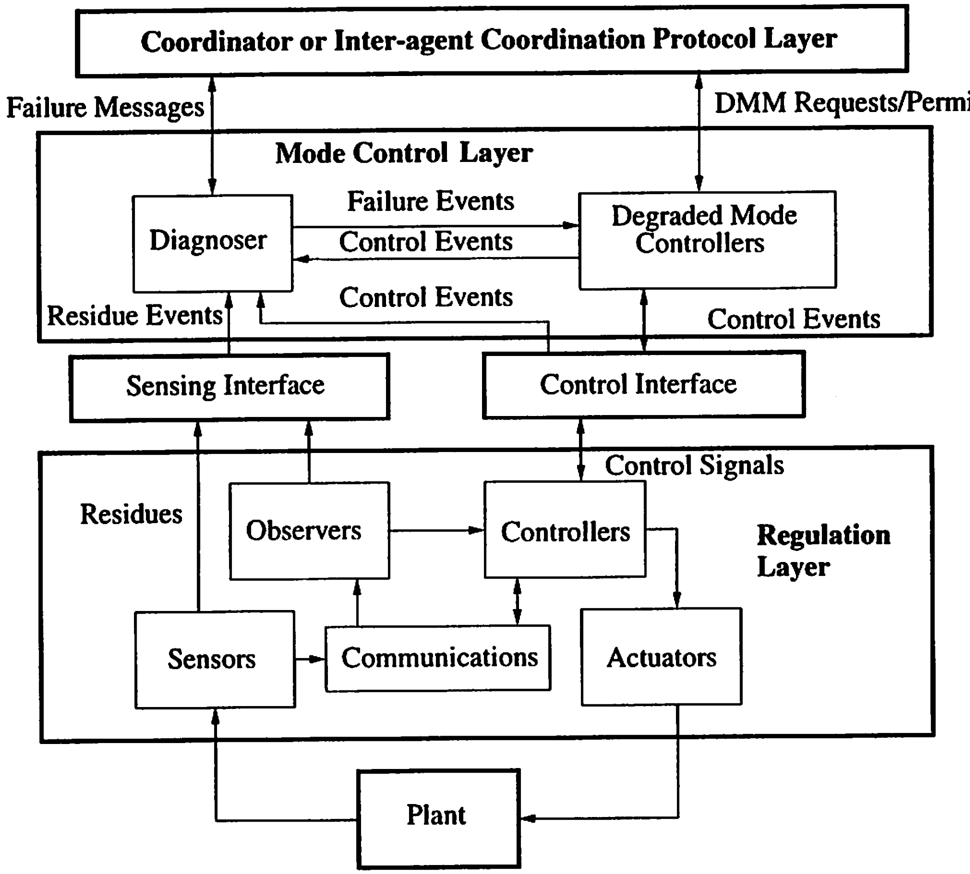
## *3.1 Platoon Follower Control*

$$u_i = (1-k_a)\ddot{x}_l + k_a\ddot{x}_{i-1} + k_v(\dot{x}_{i-1} - \dot{x}_i) + k_p(x_{i-1} - x_i - L) + c_v(\dot{x}_l - \dot{x}_i) + c_p(x_l - x_i - iL)$$

**Coordinated distributed control based on decentralized information**

**A wireless LAN supports the real-time coordination**

# 4.1 Basic Fault Management Architecture



## *5.1 Top Level Specification of Control and Observation*

$x_i$ = **boolean state of component** $i$ ($x_i = 1 \Rightarrow x_i$ **is faulty)**

$y_j$ = **boolean activation of DM maneuver** $j$

$$y_j = \wedge_{k=1}^{k=n_j}(\vee_{l=1}^{l=n_{j_k}} x_{k_l})$$

**Example:** $\Sigma_f = \{f_1, f_2, f_3, f_4\}$

$$y_j = (x_1 + x_2).(x_3 + x_4)$$

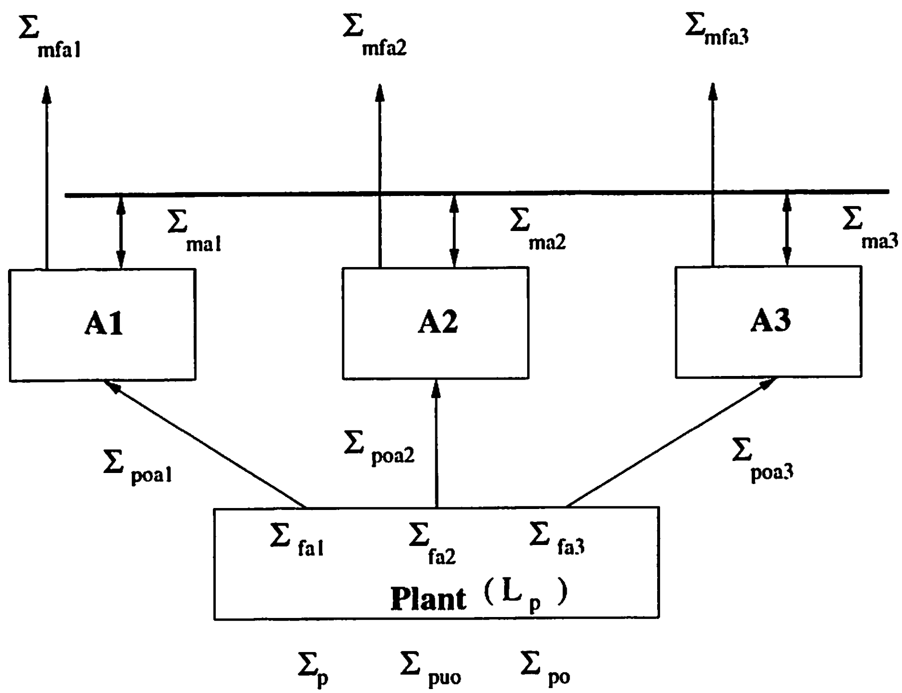
**specifies the diagnostic partition** $\{f_1, f_2\}, \{f_3, f_4\}$ **on** $\Sigma_f$.

**Top-level degraded mode control design specifies an observation problem.**

**In general use the coarsest partition that works.**

**Similar to Godbole et.al.,** *Towards a Fault Tolerant AHS Design.*

# *6.1 Diagnosis Problems in Distributed, Multi-agent Systems*




**Fully Decentralized: Can non-communicating** $A_1, A_2, A_3$ **diagnose** $\Sigma_{fa1}, \Sigma_{fa2}, \Sigma_{fa3}$ **respectively ?**

**Partially Decentralized: Can communicating** $A_1, A_2, A_3$ **diagnose** $\Sigma_{fa1}, \Sigma_{fa2}, \Sigma_{fa3}$ **respectively ?**

**Centralized: Can an observer observing** $\Sigma_{poa1} \cup \Sigma_{poa2} \cup \Sigma_{poa3}$ **diagnose the faults in** $\Sigma_{fa1} \cup \Sigma_{fa2} \cup \Sigma_{fa3}$ **?**

$L_p \subseteq \Sigma_p^*$, **plant language**

$L \subseteq \Sigma^*$, **designed observer messaging and plant system language**

$\Sigma_{mai}$, **inter-agent communication generated by** $a_i$.

$\Sigma_{poai}$, **plant observations of** $a_i$.

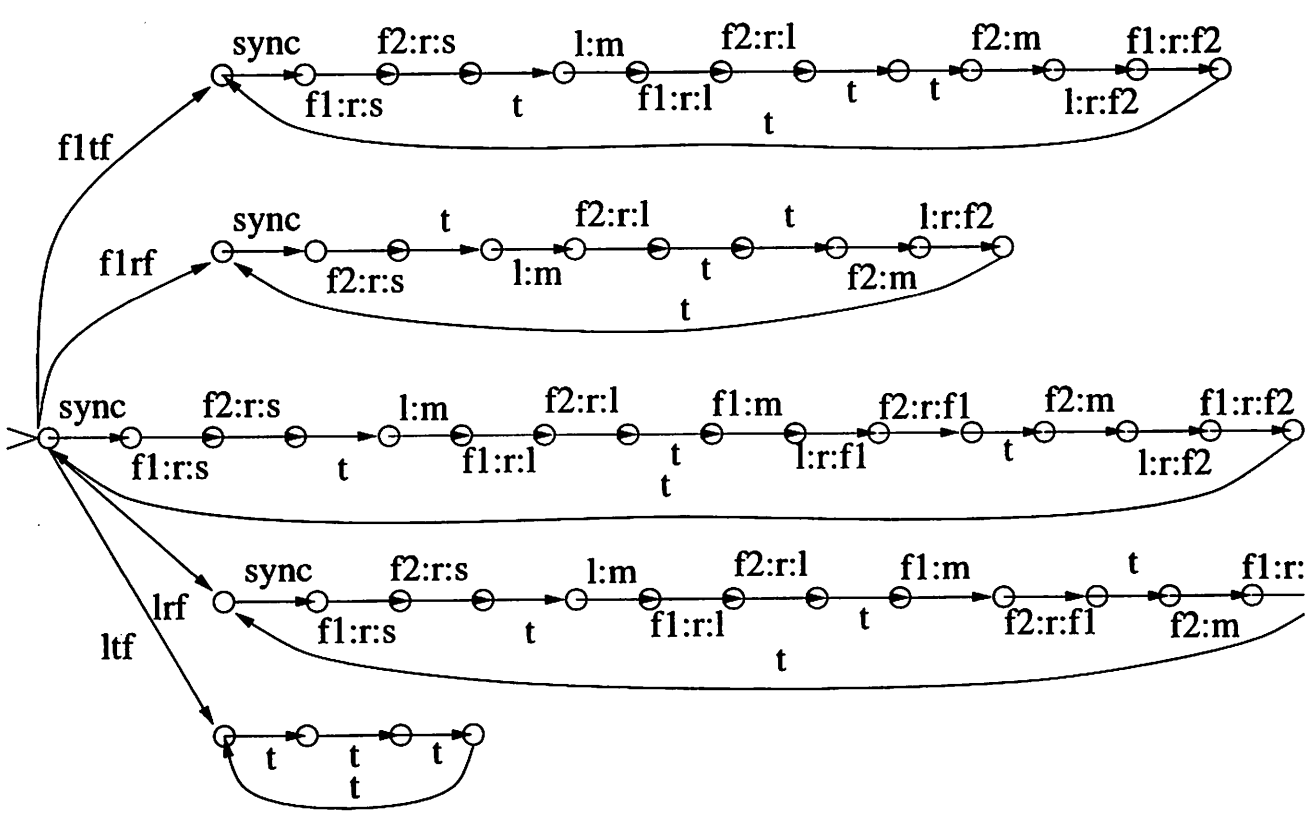
$\Sigma_{fai}$, **plant failure events of interest to** $a_i$.

$\Sigma_{mfai} \equiv \Sigma_{fai}$, **failure messages generated by** $a_i$

$$\Sigma = \Sigma_p \uplus \left(\uplus_{i=1}^{i=n} \Sigma_{mai}\right) \uplus \left(\uplus_{i=1}^{i=n} \Sigma_{mfai}\right),$$

$$\Sigma_p = \Sigma_{po} \uplus \Sigma_{puo}, \Sigma_{po} = \uplus_{i=1}^{i=n} \Sigma_{poai}, \Sigma_f = \uplus_{i=1}^{i=n} \Sigma_{fai} \subseteq \Sigma_{puo}.$$

# *6.2 LAN Example: Platoon Wireless Network*



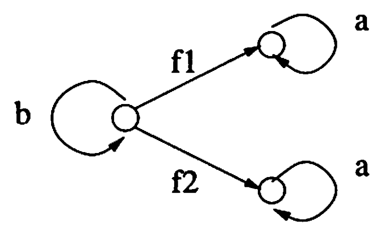
## *6.3 Modeling Assumptions*

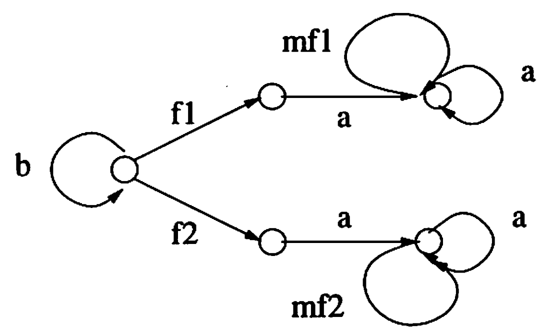
- $L, L_p$ **are prefix closed,** $L_p$ **is live**
- **Plant Consistency:** $L_p \subseteq L, P_{\Sigma_p}(L) = L_p$
- **Causality:** $\forall a_i \in \mathcal{A}, \sigma \in \Sigma_{mfai} \cup \Sigma_{mai}, u, v \in L,$

$$(u\sigma \in L) \wedge (P_\Gamma(u) = P_\Gamma(v)) \Rightarrow v\sigma \in L$$

$\Gamma = \Sigma_{poai} \uplus \Sigma_m \uplus \Sigma_{mfai}$

- **A non-causal design:** $\Sigma_{puo} = \{f_1, f_2\}$



## 6.4 Definitions

$L$ is $a_i$-detecting iff for all $\sigma_{fai} \in \Sigma_{fai}, u, v \in \Sigma^{ast}, |P_{\Sigma_p}(v)| \geq n_{ai}, u\sigma_{fai}v \in L$, $\sigma_{mfai} \in u\sigma_{fai}v$ or there exists $t \in (\Sigma_m \cup \Sigma_{mf})^*$ such that $u\sigma_{fai}vt\sigma_{mfai} \in L$.

$L$ is $a_i$-false alarm free iff for all $u\sigma_{mfai} \in L, \sigma_{fai} \in u$.

$L$ is $a_i$-correct iff $L$ is $a_i$-detecting and $a_i$-false alarm free.

- A detecting language always exists for every $L_p$.

$$L = \{u : u \in L_p, u = v\sigma_1, \ldots \sigma_k, v \in L_p\}, \Sigma_{mfai} = \{\sigma_1, \ldots \sigma_k\}$$

- A false alarm free $L$ always exists, $L = L_p$.
- Similar to the Neyman-Pearson problem.
- Similar to diagnosability in the DES literature.
- Detecting languages with false alarms are a useful concept.
- Purpose: Existence and synthesis of correct $L$.

## *6.5 Centralized Diagnosis (Previous Work)*

**Theorem 1** *For* $(L_p, \Sigma_{po}, \Sigma_f, \Sigma_{puo})$ *there exists correct* $L$ *iff there exists* $n \in \mathbb{N}$ *such that for all* $\sigma_f \in \Sigma_f, u\sigma_f v \in L_p, |v| > n$,

$$w \in P_{\Sigma_p}^{-1}(P_{\Sigma_{po}}(u\sigma_f v)) \cap L_p \Rightarrow \sigma_f \in w.$$

**Assume $L_p$ is regular, generated by $G_p$, and $G_p$ has no unobservable event cycles.**

**Then construct the *diagnoser FSM* $G_d$, i.e., the finite state observer of $G_p$ that extracts all possible information about $\Sigma_f$ from observation of $\Sigma_{po}$.**

**Theorem 2** *There exists correct* $L$ *iff for each* $\sigma_f \in \Sigma_f$ *there are no* $\sigma_f$*-indeterminate cycles in* $(G_p, G_d)$.

## 6.6 Partially Decentralized Diagnosis

**Theorem 3** *For* $(L_p, \{\Sigma_{poai}, \Sigma_{fai}\}_{a_i \in \mathcal{A}}, \Sigma_{puo})$ *there exists correct* $L$ *iff there exists* $n \in \mathbb{N}$ *such that for all* $\sigma_f \in \bigcup_{i=1}^{i=n} \Sigma_{fai}, u\sigma_f v \in L_p, |v| \geq n,$

$$(w \in L_p) \wedge (\forall a_i, P_{\Sigma_{poai}}(w) = P_{\Sigma_{poai}}(u\sigma_f v)) \Rightarrow (\sigma_f \in w).$$

**Assume $L_p$ is regular, generated by $G_p$, and $G_p$ has no unobservable event cycles.**

**For each $a_i$ construct the diagnoser $G_{dai}$. Let**

$$G_d = (\otimes_{i=1}^{i=n} G_{dai}) \otimes G_{po}, q_d = \cap_{i=1}^{i=n} q_{dai}.$$

**Theorem 4** *There exists correct* $L$ *iff for each* $\sigma_f \in \Sigma_{fai}, a_i \in \mathcal{A}$, *there are no* $\sigma_f$*-indeterminate cycles in* $(G_p, G_d)$.

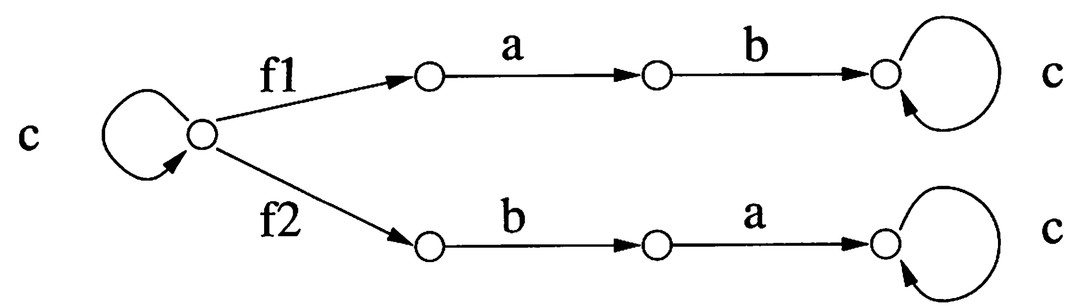
## 6.7 Centralized vs. Decentralized

$\Sigma_{po1} = \{a, c\}, \Sigma_{f1} = \{f1\}, \Sigma_{po2} = \{b, c\}, \Sigma_{f2} = \{f2\}$

**The faults can be centrally diagnosed.**

**For the given decentralization of information there is no messaging scheme that can diagnose the faults.**

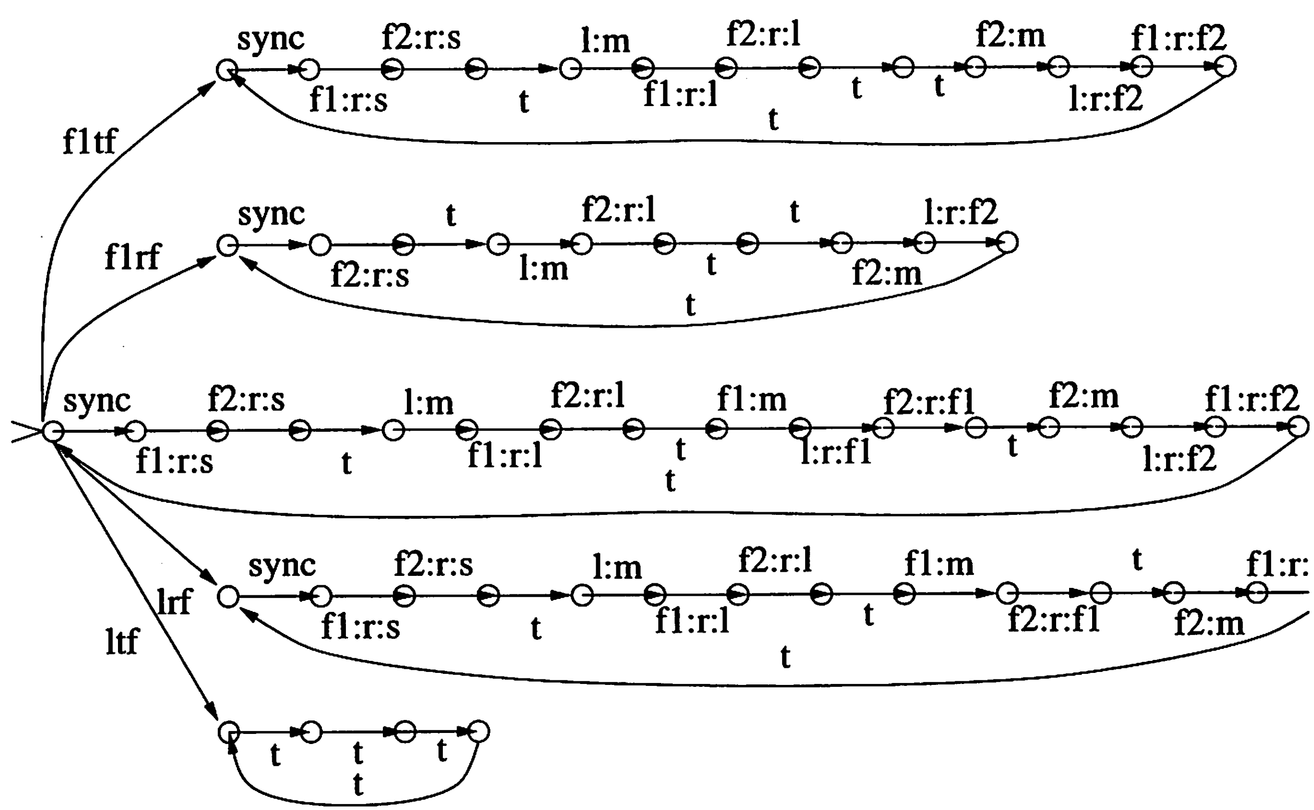
$$u\sigma_f v = f1abc^n, w = f2bac^n, P_{\Sigma_{oi}}(u\sigma_f v) = P_{\Sigma_{oi}}(w), f1 \notin w$$



## 7.1 LAN Example: Platoon Wireless Network

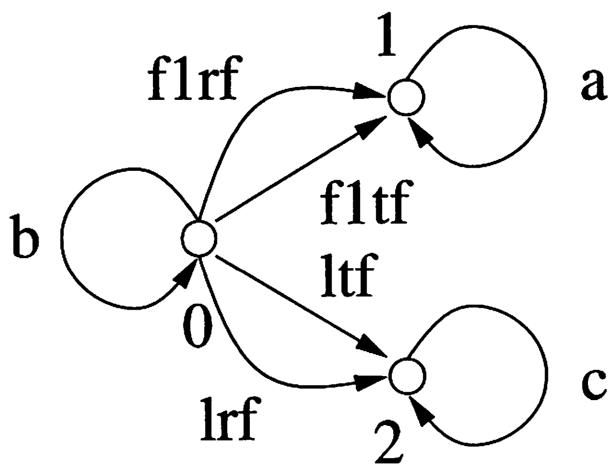
$$\Sigma_{ol} = \{tick, lrf1, lrf2\}, \Sigma_{of1} = \{tick, f1rl, f1rf2\}, \Sigma_{of2} = \{tick, f2rf1, f1rf2\},$$
$$\Sigma_{fl} = \{ltf, lrf\}, \Sigma_{ff1} = \{f1tf, f1rf\}, \Sigma_{ff2} = \{f2tf, f2rf\}$$

**All faults can be centrally diagnosed.**

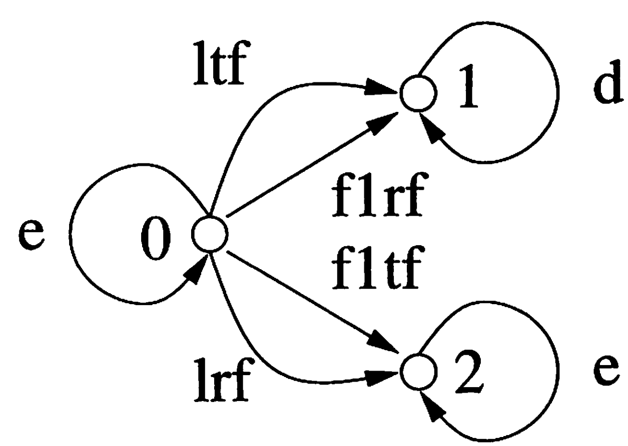


## *7.2 LAN Example: Plant Abstraction*

**Assume also that lead and follower observations alternate.**

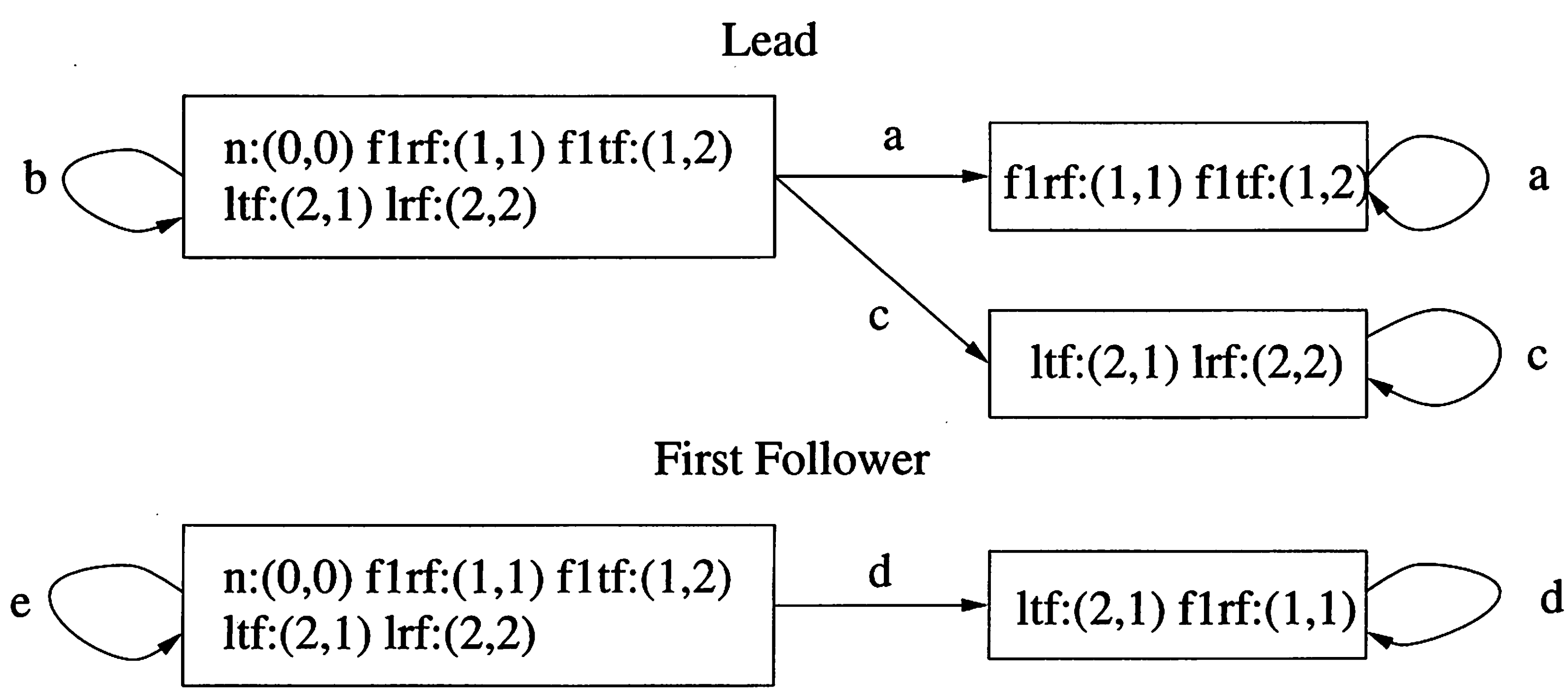



Lead

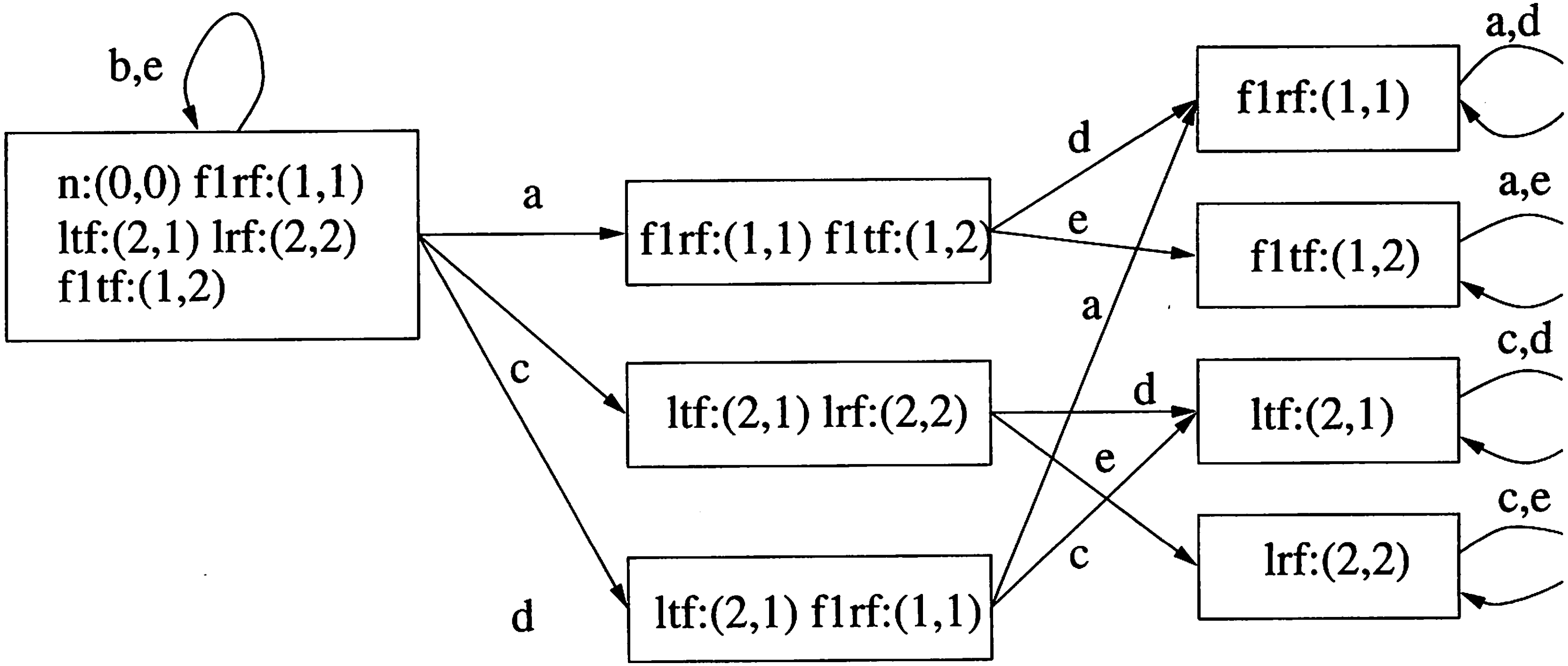



First Follower

## *7.3 LAN Example: Individual Diagnosers*



## *7.4 LAN Example: A diagnostic messaging scheme exists*



## 7.5 Fully Decentralized Diagnosis

**Assume $L_p$ is regular and each cycle in $G_p$ has at least one event from each $\Sigma_{poai}$.**

**Theorem 5** *There exists $L$, $a_i$-correct for all $a_i$, $P_{\Sigma_m}(L) = \emptyset$ iff for all $a_i$ and for all $\sigma_f \in \Sigma_{fai}$, there are no $\sigma_f$ indeterminate cycles in $(G_{dai}, G_p)$.*

## *7.6 Future Work*

- **Design of efficient messaging schemes for decentralized detection.**
- **Probabilistic design and verification of detecting languages with false alarms.**
- **Hybrid Degraded Mode Control Design.**
- **Inter-agent coordination design for distributed observation and control.**
- **Hierarchical specification and design of observation and control.**