Diagnosis of Complex Systems: Bridging the Methodologies of the FDI and DX Communities

THE PROLIFERATION of new technologies has significantly increased the complexity of human designed systems. Nowadays, complex technological systems are embedded, i.e., they contain tightly coupled hardware and software systems. Typical examples are controlled systems, such as manufacturing plants, aircraft, and spacecraft. Maintaining safety, reliability, and uninterrupted operation of these systems have become very important issues. The goal of diagnosis is to identify the primary causes (faults) of a set of observed symptoms (deviations from nominal in system behavior) that indicate degradation and failure in system components leading to abnormal system performance. Given the importance of this problem for safety-critical systems, a broad spectrum of approaches has been developed to cope with the diversity and complexity of the diagnosis task. To further advance the state of the art and address the difficult problems, it has become critical to learn how to use all these methods in synergistic and optimal ways.

Our focus in this Special Issue is on model-based approaches to diagnosis. Broadly speaking, there are two distinct and parallel research communities that work on model-based approaches.

- The **Fault Detection and Isolation (FDI)** community, which bases the foundations of its solution approaches on engineering disciplines such as control theory and statistical decision making, and
- The **Diagnosis (DX)** community, which bases the foundations of its solution approaches from the fields of computer science and artificial intelligence.

Each community has developed its own terminology, tools, techniques, and approaches to solve diagnosis problems. In the past, there has been very little communication between these two communities, but recently, there has been a growing number of researchers who are trying to understand and incorporate approaches from the parallel research fields to build better and more effective diagnostic systems.

This Special Issue of the IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS—PART B: CYBERNETICS highlights these recent exchanges and the results of the collaboration of the two communities. This has resulted in significant moves to develop a common terminology for fault diagnosis, and to identify the similarities and the complementary features in the problem definitions and problem solutions developed by the two communities. The goal is to contribute toward a unifying framework, which will enable researchers and practitioners to take advantage of the synergy in the complementary techniques employed in engineering and computer science.

We believe that the primary topics that will facilitate the building of bridges between the two communities can be loosely organized into the following categories.

1) Classification of diagnostic problems and diagnostic approaches that span the FDI and DX communities.
2) Tutorial papers that cover the state of the art and provide a comparative analysis of FDI and DX approaches.
3) Theoretical comparisons of FDI and DX approaches.
4) Empirical studies using nontrivial examples to compare the effectiveness and shortcomings of a set of DX and FDI approaches.
5) Development of novel problem solving methodologies that combine FDI and DX techniques.

Several groups are currently working on the above and related topics. Representative sites for BRIDGE material are as follows.

- The BRIDGE group, funded by the Monet Network in the European community (http://monet.aber.ac.uk/). Papers presented at a special BRIDGE workshop held in conjunction with the 12th International Workshop on Principles of Diagnosis on March 5th–6th, 2001 in via Lattea, Italy, can be found on the website, http://www.di.unito.it~dx01 under "Bridge Workshop".
- The French IMALAIA group, supported by CNRS (http://www.univ-lille1.fr/s3/ under *"Projets en cours", "Projet 1"*).
- The European DAMADICS Research and Training Network (http://www.eng.hull.ac.uk/research/control/act/damadics1.htm).

A number of papers submitted to the IFAC Safeprocess symposia and the International Workshop on Principles of Diagnosis have also covered BRIDGE issues, and a significant step toward integration was achieved by co-locating the IFAC-sponsored Safeprocess'03 Symposium and the 2003 Principles of Diagnosis Workshop in Washington, DC, and running a number of special BRIDGE sessions at this meeting.

The 18 papers submitted to this Special Issue reflect the state of the art in the FDI/DX Bridge area. Six high-quality articles have been selected by the Guest Editors after a careful review process. At least three independent reviewers and one of the Guest Editors reviewed each paper. Each of the selected papers went through a revision and a second review. The papers are representative of approaches that provide bridges between the parallel FDI and DX communities. They include innovative and novel approaches that demonstrate effective results, and provide solutions that go beyond the traditional techniques developed within each community. Equally important for this Special Issue, the papers have met strong requirements concerning clarity of terminology that bridges the two communities. Topics 2, 3, and 5 are covered well in the selected set, with the stress on the category 5, i.e., novel problem-solving methodologies that

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combine FDI and DX techniques. A brief description of the six selected papers follows.

The paper by Cordier *et al.* provides a theoretical comparison of the DX and FDI approaches (category 3). This paper establishes links between the concepts that underlie the FDI analytical redundancy approach and the DX consistency-based logical approach. In particular, the link between *structured parity equations* or *analytical redundancy relations* (ARR) and *conflicts* (in the sense of Reiter) is clarified by introducing the notions of *potential conflict* or *ARR support*, and a conflict is interpreted as the support of a non satisfied ARR. A formal framework is proposed for comparing the two approaches. The role of completeness properties on the set of ARRs is highlighted and the formal match of the two approaches is proved under completeness conditions.

The Hofbaur and Williams paper develops a novel problem solving methodology (category 5) in the context of hybrid systems, i.e., systems that have continuous as well as discrete dynamics. This naturally calls for bridging techniques. This paper approaches the problem of tracking hybrid systems behavior evolution using a multiple-model estimation scheme that employs a bank of Kalman filters (a typical FDI tool), one for each mode, and probabilistic merging. The complexity of standard multiple-model estimation when applied to highly interconnected component systems is examined and model-based search techniques, typically used by the DX community are proposed to focus the continuous estimation onto the set of most likely modes.

The Pulido and Alonso paper develops a novel problem-solving methodology (category 5) for conflict generation within the consistency-based diagnosis framework. It uses the *possible conflict* concept (equivalent to *potential conflict* in Cordier *et al.*), which is characterized within a hypergraph framework to propose an off-line compilation technique of dependencies as an alternative to on-line dependency recording. Possible conflicts generated using this technique are compared with those obtained by the traditional DX diagnosis engine GDE and other compilation techniques that are employed by the FDI community.

Gentil *et al.* provide a comparative discussion of the FDI and DX approaches and proposes an on-line diagnosis method that combines tools from both communities. Therefore, part of the paper hence falls into the second category and the rest of the paper can be put in the fifth category. The diagnosis method is based on a model, which relies on both a qualitative causal representation of the process, a methodology commonly used in the DX community, and quantitative local models, as those used by the FDI community, attached to every causal influence. At the local level, standard FDI techniques for numeric residual evaluation are used. At the global level, diagnostic reasoning is supported by the causal structure, and the similarities between this method and DX component-oriented reasoning methods are established.

The Lamperti and Zanella paper differs from the other five papers because it uses a discrete-event systems (DES) model for diagnostic analysis. The paper bridges complementary approaches from the two communities, namely the diagnoser approach and active system approach. It is a nice example of how to take advantage of two approaches that have been developed from different backgrounds to overcome the limitations of the individual approaches. The approach can also deal with an extended class of DESs that show synchronous and asynchronous behavior. Their diagnostic method accepts the same inputs and produces the same outputs as the diagnoser approach but it does not need the global model of the system from component models, which means that it can be applied to complex systems without computational intractability. Diagnosis is carried out on-line and the graph supporting monitoring and diagnosis reasoning is generated incrementally upon occurrence of an observable event.

The Rinner and Weiss paper deals with monitoring an uncertain continuous dynamic system, and is another nice example of a novel problem solving methodology (category 5). The scope of the paper is restricted to fault detection. Continuous dynamic systems are the main focus of the FDI community, which generally handles uncertainty within a stochastic framework. In contrast, this paper represents uncertainty in the form of bounded value parameters following an approach that has been initiated in the DX community. The originality of the approach is to use measurements against model-based predictions to refute inconsistent parts from the uncertainty space of the model. In doing so, the model's uncertainty space is refined through refutation, which comes back to incrementally provide a better estimation of the model's parameters. (*Due to an unfortunate logistic error, this paper has appeared in the October 2003 issue of the journal*).

We hope that this Special Issue demonstrates that bridge research in FDI/DX bridge has already gone beyond the initial analysis and comparison steps, and is now is mature enough to attract researchers who develop more novel methods that exploit the synergism between the FDI and DX approaches. Finally, the Guest Editors would like to thank the authors for their high-quality submissions, the anonymous reviewers for their diligent reviews of all of the papers, and the Editor-In-Chief, Prof. Larry Hall, for his help and patience in putting the Special Issue together.

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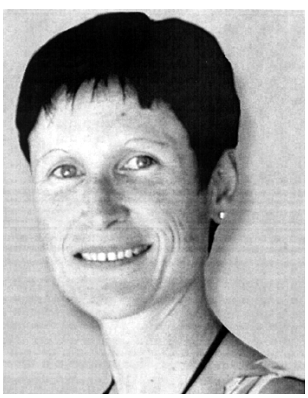

Marie-Odile Cordier was born in Paris, France, in 1950. She received the Ph.D. degree in computer science in 1979 and the Habilitation à Diriger des Recherches in 1996, both from the University of Paris Sud/Orsay, Sud/Orsay, France.

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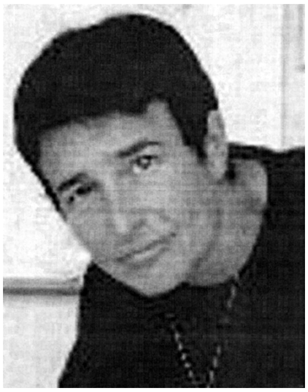

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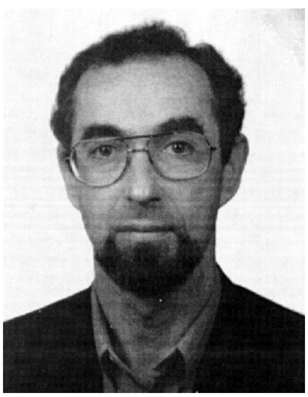

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