Decision-Theoretic Diagnosis-Repair Planning Using Bayesian Networks

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Abstract: Common diagnosis systems view the accurate identification of components responsible for the faulty behavior of the system as the ultimate goal of the diagnostic activity. Restoring the system to its functioning state is a secondary concern that is not explicitly addressed during the fault identification process. In this article, we take the restoration of the system to be our ultimate objective and ,thus, the diagnosis is important only to the extend that it contributes to derive a repair plan with minimal expected cost. Both in case of a single fault and multiple-independent faults, we build on existing approaches for repair planning to construct an algorithm for scheduling repair actions. Encoding our knowledge about the system in a *Bayesian network*, we, then, account for the possibility of sensing using an approximation algorithm based on limited look-ahead evaluation of pending sources of information based on their degree of *informativeness* and associated costs.

1 Introduction

Although much work exists on diagnosis [1; 2], only recently attention turned to the synergy that can develop when integrating diagnosis and repair [3]. Conventional diagnosis system focus on mechanisms for faults isolation, and the restoration of the system is only a secondary concern that is not explicitly addressed during the fault isolation process. Taking the restoration of the system to be our ultimate goal, existing methods on diagnosis would generally result in *sub-optimal* plans since they implicitly schedule the repair actions in final steps.

In this article, we view the diagnosis and repair planning as two complementary activities that interact in order to restore the system to its functioning state. A planner computes the optimal ordering of observation or repair actions for systems with a single fault or multiple independent faults. Before execution of an action, pending sources of information are evaluated and the agent chooses, if any, the one that contributes considerably to minimize the repair plan.

2 Optimal Repair Planning

The main goal of diagnosis is to generate a low cost repair plan for the faulty system, where a plan consists of observations and component-repair actions. In this section, we focus only on repair actions.

Let us consider a system with n components denoted by the set $\{ C_1, \ldots, C_n \}$ for which we want to develop an optimal repair plan. We assume that each component C_i can be exactly in either of two states: it is working properly, denoted by $C_i = ok$, or it is failing, denoted by $C_i = \neg ok$. Each component C_i can be observed incurring a cost c_i^o, and repaired with a cost c_i^r. Let p_i denote the probability the component C_i is faulty. If we repair the components sequentially in the order $\{C_1, \ldots, C_n\}$, and let $\Pi(1, \ldots, n)$ denote this repair plan, depending on the location of faulty components in the repair sequence, we incur different costs up to restoring the system. Specifically, under the plan $\Pi(1, \ldots, n)$ the expected cost of repair, $EC(\Pi)$ is given by :

$$EC(\Pi) = \sum_{i=1}^{n} c_i^r \Big(1 - P(C_i = ok, \ldots, C_n = ok)\Big) \quad (1)$$

For instance, under the single fault assumption, the above equation simplifies to:

$$EC(\Pi) = \sum_{i=1}^{n} \Big(\sum_{k=i}^{n} p_k\Big) c_i^r \quad (2)$$

For any given plan $\Pi(1, \ldots, i, i+1, \ldots, n)$, swapping the position of any two consecutive components, say C_i and C_{i+1}, and keeping the position of all other components intact, we get another repair plan $\Pi(1, \ldots, i+1, i, \ldots, n)$ that is dominated by $\Pi(1, \ldots, i, i+1, \ldots, n)$ if its expected cost $EC(\Pi(1, \ldots, i, i+1, \ldots, n))$ is bigger than the expected cost of the initial plan $EC(\Pi(1, \ldots, i+1, i, \ldots, n))$. Note that the $EC(\Pi(1, \ldots, i, i+1, \ldots, n)) - EC(\Pi(1, \ldots, i+1, i, \ldots, n)$ has a simple form, since it contains only c_i^r, c_{i+1}^r,p_i and p_{i+1}. We

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can easily show that, under single fault assumption, $\Pi(1,\ldots,i,i+1,\ldots,n)$ is optimal if and only if for all adjacent components, say C_i and C_{i+1}, satisfy:

$$\frac{p_i}{c_i^r} \geq \frac{p_{i+1}}{c_{i+1}^r} \tag{3}$$

Following the same line of reasoning, and noticing that under assumption of multiple independent faults the equation (1) simplifies to:

$$EC(\Pi) = \sum_{i=1}^{n} c_i^r \Big(1 - \Pi_{k=i}^{n}(1-p_i)\Big) \tag{4}$$

We can easily show that the optimal repair plan is obtained by ordering the ratios:

$$\frac{p_i}{c_i^r(1-p_i)} \geq \frac{p_{i+1}}{c_{i+1}^r(1-p_{i+1})} \tag{5}$$

We sequentially repair the components C_i according to the ratio $\frac{p_i}{c_i^r(1-p_i)}$ until the system is restored.

Accounting for inspection before repair is straightforward. If the agent first inspects the components before repair, the results obtained in this section are only slightly amended. Namely, we substitute the the cost of repair c_i^r by cost of observation c_i^o. Another possible extension is to derive the globally optimal plan that partitions the components into a set of components to be observed before repair and a set components to be repaired without prior observation.

3 Integrating Diagnosis and Repair

Up to this point we restricted the action available to the agent to repair actions only. In many cases, the agent has the possibility to take sensing action that may reduce its uncertainty about the state of the world. For example, in troubleshooting a car, we have the possibility to check whether radio is working properly or not. This action reveals some information about the state of some other components, say for example battery.

We adopt an approximation method for scheduling sensing and repair actions. It is based on a *limited lookahead* evaluation of pending sources of information. The approach evaluate each sensing action based on its cost and degree of *informativeness*. Specifically, At each decision point, each sensor S_j, that we represent as a node in a Bayesian network[4], is instantiated to all its possible values s_i^j and the probability of failure of different components is updated, given that S_j is equal to s_i^j. We compute the optimal repair plan as derived using equation (5). Let $\Pi(s_i^j)$ this plan, and $c(S_j)$ denote the cost of observing the sensor S_i. The true value of S_j is unknown a priori, it follows then that the expected repair plan accounting for the possibility of observing S_j, denoted $\Pi(S_j)$, is obtained by weighting $\Pi(s_i^j)$ for all s_i^j by the probability of observing the event $S_j = s_i^j$. Adding the cost of sensing S_j we obtain:

$$EC(\Pi(S_j)) = c(S_j) + \sum_{i=1}^{l_j} \Big(\Pi(s_i^j) P(S_j = s_i^j)\Big) \tag{6}$$

Where l_j is the number of states the sensor S_j can take. To decide on which action to take, we compute the difference between the repair plan when no sensing action, denoted $\Pi(\emptyset)$, with the repair plans $\Pi(S_j)$ accounting for possible sensing for each sensor S_j. We choose to consult the sensor that yields an expected cost repair plan $EC(\Pi(S_j))$ less than $EC(\Pi(\emptyset))$. If no such sensor exist, we take the repair action as indicated by the plan $\Pi(\emptyset)$. We submit the new observation made about the system as evidence in the Bayesian network, and the process is iterated, while accounting for available knowledge, until the system is restored.

4 Conclusion

This paper introduced a tractable algorithm for diagnosis-repair planning where the agent goal is not to increase its knowledge, but rather to choose a sequence of actions that would restore the faulty system with minimal expected cost. Heckerman[5] presented a solution to the diagnosis-repair problem assuming a single fault and each component is first observed before repair. Srinivas [6] presented an algorithm that computes off-line the optimal repair plan. He exploits the hierarchical description of the modeled system, assuming that each component has only a small number of subcomponents to allow an exhaustive search. The algorithm presented here is a a straightforward extension of this two works. Namely, we do not assume a single fault thus generalizing [5] and we count for the possibility of sensing, that [6] does not.

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