Techniques Used to Design Reliable Control Systems. 
A Case Study: Electrical Geothermal Plant from the University of Oradea, Romania

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ABSTRACT
The demands placed upon control systems in respect to reliability continue to increase as these systems become integrated into a wide variety of safety-critical applications. For these categories of applications, it is essential to be able to guarantee that all critical processing is accomplished accurately and on time Adan and Magalhaes and Ramamritham (1998).

Consequently, the increasing complexity of the real-time control systems demands for new techniques that can be applied during all the development phases of the system. This paper presents a set of steps, concepts and criteria that can be used for critical real time process control design; consequently, an increased reliability can be achieved Irwin (1996).

An example of how these concepts were used in order to design a highly reliable real-time control system is presented using a case study: the electrical geothermal plant from the University of Oradea. The paper outlines the fact that the proposed techniques address one of the most important issues regarding real-time control systems design: reliability. It also provides a structured, disciplined and highly visible development Puchol and Mok (1998).

1. INTRODUCTION
Generally, real-time control systems are critical and expensive to build. Moreover, they are costly to run due to the hardware costs and manpower requirements Zmaranda and Cretu (2000). Therefore, it is highly desirable to test as much on the system’s design as possible prior to its actual implementation. Moreover, the usual approach should be dynamic testing, which implies testing during all the development phases Bequette (1998).

Among several testing phases, a very important issue is design testing. For critical systems, the reliability testing is crucial during design phases: and this could be done using reliability/availability diagrams, which are different from the system’s functional schemes. It is important to achieve an overall view about system’s reliability and availability from the early stages of the design Svrcek and Mahoney and Young (2000).

2. STEPS IN RELIABILITY ASSESSMENT
The following steps should be followed in the reliability assessment process:
- divide the system into three basic levels: system level, subsystem/module level and component level Goble (1992).
- For reliability analysis purpose all these three level of a system should be considered. Proper cognizance is routed in the lowest level of the system
- reliability model construction based on system’s physical model, its operation and failure modes. In the reliability model components may be connected differently from the physical model Johnson (1993)
- reliability/availability calculation, evaluation and analyzing using the rules of probability. For non-reparable system reliability will be considered; for repairable systems, availability is used in turn Kercecioglu (1991).
- finalize the assessment process by proposing some improved reliability schemes using redundant components Leitch (1995)

3. ORADEA GEOTHERMAL POWER PLANT RELIABILITY ASSESSMENT
3.1. SYSTEM OVERVIEW
The geothermal power plant is a component of the cascaded geothermal energy utilization system, and is used to convert the energy of the geothermal water into electrical energy using CO₂ as working fluid. The elements of the power plant are the following: vaporizers (heat exchangers used to vaporize the CO₂), a reciprocating engine connected with the electric generator, a make-up and expansion CO₂ tank, condensers (heat exchangers used to condense the CO₂) and a CO₂ pump.

As mentioned above the geothermal power plant uses CO₂ as a working fluid. The thermodynamic cycle presented in Figure 1 shows the different evolution stages of the working fluid and it has to ensure the heat transfer between CO₂ and the geothermal water or cold water.

![Figure 1. Thermodynamic cycle of the working fluid](image-url)
The evolution from state 1 to 2 represents the expansion of the CO₂ inside the engine generating mechanical work that is transformed into electrical energy; 2 to 3 transition represents the evolution of CO₂ inside condensers where the heated CO₂ is used to heat the cold water and has three distinct sub phases (see Figure 1); 3 to 4 state transition is the compression of CO₂ into the CO₂ liquid pump; the 4 to 1 transition represents the CO₂ evolution inside the vaporizers where the gas is heated through the heat exchanger using geothermal water.

3.2. CONTROL SYSTEM STRUCTURE

The control system scheme for the thermodynamic cycle of the geothermal power plant is shown in Figure 2.

The control system has to maintain constant the CO₂ pressure and temperature in all the important states of the thermodynamical cycle Smith and Corripio (1997).

As it can be seen from Figure 1 it is enough to maintain constant the temperature and pressure in states 1 and 3 because the 3 to 4 transition is an adiabatic compression and the transition from 1-2 is an adiabatic expansion. In order to control the thermodynamical cycle it’s enough to control the CO₂ temperature $t_1$ after vaporisation in the heat exchangers (at the engine admission) and $t_3$ the CO₂ temperature at the after condensation into the heat exchangers.

We have also to control $h$ the CO₂ liquid level from the tank in order to insure an accurate CO₂ pump functioning (Figure 2).

Table 1 contains the main control loops from the geothermal power plant together with the controlled parameter tendency and the expected reaction of the system Gabor and Gavrilescu (2002).

Figure 3 shows the logical scheme used in order to control the $t_3$ temperature Phillips and Harbor (1996).

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**Table 1. Control loops in the power plant**

<table>
<thead>
<tr>
<th>Controlled parameter /loop</th>
<th>Parameter tendency</th>
<th>Expected reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_1$/TT1,RA1,RB1, vaporizers</td>
<td>Increases</td>
<td>- geothermal water flow rate decreases</td>
</tr>
<tr>
<td>$t_1$/TT1,RA1,RB1, vaporizers</td>
<td>Decreases</td>
<td>- geothermal water flow rate increases</td>
</tr>
<tr>
<td>$t_3$/TT3,RA2,RB2, condensers</td>
<td>Increases</td>
<td>- CO₂ pump speed decreases</td>
</tr>
<tr>
<td>$t_3$/TT3,RA2,RB2, condensers</td>
<td>Decreases</td>
<td>- CO₂ pump speed increases</td>
</tr>
<tr>
<td>$h$/IN,RA2,RB2,condensers</td>
<td>Increases</td>
<td>- cold water flow rate decreases</td>
</tr>
<tr>
<td>$h$/IN,RA2,RB2,condensers</td>
<td>Decreases</td>
<td>- cold water flow rate increases</td>
</tr>
<tr>
<td>$h$/IN,RA2,RB2,condensers</td>
<td>Decreases</td>
<td>- CO₂ pump speed decreases</td>
</tr>
</tbody>
</table>
Figure 3: The logical scheme used to control the $t_3$ temperature

Figure 4: Reliability scheme for the geothermal power plant

Figure 5: Reliability scheme for the temperature $t_3$ controlled subsystem

Figure 6: Reliability scheme for condensers

Figure 7: Reliability scheme for the temperature $t_3$ controlled subsystem using redundancy
3.3 RELIABILITY AND AVAILABILITY ASSESSMENT

3.3.1. Reliability model construction

In order to be able to study the control system’s behavior presented in Figure 2 from reliability or availability point of view first we have to implement realistic and credible reliability/availability schemes Bentley (1999).

Figure 4 shows at systems and block level the reliability scheme for the thermodynamic cycle of the geothermal power plant (first level considered). The subsystems of the controlled loops implemented are controlled using a PLC (the control subsystem).

The second phase considers the reliability/availability scheme (shown in Figure 4) detailed at subsystem level. Figure 5 shows the detailed reliability/availability scheme for temperature t3 controlled subsystem. This subsystem is delimited in Figure 2 using a dotted black line. The data gathered for the other subsystem from Figure 2 are not presented into details in this paper.

If we take a look to the structure from Figure 5 it can be seen that the main critical points are represented by the flow actuator (motor M + RB2) and the temperature transducer TT3. At component level, the reliability scheme is shown in Figure 6, which considers all its elements.

3.3.2. Reliability/availability analysis

In order to obtain a higher value for the reliability/availability for the temperature t1 controlled subsystem we proposed the redundant scheme from Figure 7. We obtained this scheme including in the scheme shown in Figure 4 extra entities (we doubled the flow actuator and the temperature transducer TT3). At component level, the reliability scheme is shown in Figure 6, which considers all its elements.

![Condensers](image1)

**Figure 8: Reliability/availability for condensers**

Based on the scheme from Figure 6, a comparison between choosing nonrepairable/repairable components should be done. Figure 8 shows that better results could be obtained by using repairable elements (availability is greater than reliability).

In order to compare the reliability or availability of the schemes presented in Figure 5 and Figure 7 we consider the individual failure and repair rates shown in Table 2.

### Table 2: Individual failure and repair rates

<table>
<thead>
<tr>
<th>ELEMENTS OF t3 TEMPERATURE CONTROLLED SUBSYSTEM</th>
<th>INDIVIDUAL RATES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \lambda ) [week(^{-1})]</td>
</tr>
<tr>
<td>C1+C2 CO2 pipes</td>
<td>0.000228</td>
</tr>
<tr>
<td>Cold water pipes</td>
<td>0.000225</td>
</tr>
<tr>
<td>C1+C2 CO2 pipes – cold water pipes connection</td>
<td>0.000215</td>
</tr>
<tr>
<td>C1+C2 CO2 pipes casing</td>
<td>0.000182</td>
</tr>
<tr>
<td>Cold water pipes casing</td>
<td>0.00018</td>
</tr>
<tr>
<td>C1+C2 CO2 pipes casing - cold water pipes casing connection</td>
<td>0.000175</td>
</tr>
<tr>
<td>RB2 (*)</td>
<td>0.000154</td>
</tr>
<tr>
<td>Motor of RB2 (*)</td>
<td>0.000057</td>
</tr>
<tr>
<td>PLC - motor of RB2 connection (*)</td>
<td>0.00021</td>
</tr>
<tr>
<td>TT3 (***)</td>
<td>0.00012</td>
</tr>
<tr>
<td>PLC – TT3 connection (***)</td>
<td>0.000156</td>
</tr>
</tbody>
</table>

Based on individual failure and repair rates presented in Table 2, in Table 3 it is estimated the availability for two distinct cases: for the reliability scheme from Figure 5 (without redundancy) and for the reliability scheme from Figure 7 (with redundancy).

### Table 3: Comparative availability values

<table>
<thead>
<tr>
<th>ELEMENTS OF t3 TEMPERATURE CONTROLLED SUBSYSTEM</th>
<th>A (with redundancy)</th>
<th>A’ (without redundancy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1+C2 CO2 pipes</td>
<td>A1 = 0.99453</td>
<td>A1’ = 0.99453</td>
</tr>
<tr>
<td>Cold water pipes</td>
<td>A2 = 0.99222</td>
<td>A2’ = 0.99222</td>
</tr>
<tr>
<td>C1+C2 CO2 pipes – cold water pipes connection</td>
<td>A3 = 0.95877</td>
<td>A3’ = 0.95877</td>
</tr>
<tr>
<td>C1+C2 CO2 pipes casing</td>
<td>A4 = 0.99563</td>
<td>A4’ = 0.99563</td>
</tr>
<tr>
<td>Cold water pipes casing</td>
<td>A5 = 0.99570</td>
<td>A5’ = 0.99570</td>
</tr>
<tr>
<td>C1+C2 CO2 pipes casing - cold water pipes casing connection</td>
<td>A6 = 0.96619</td>
<td>A6’ = 0.96619</td>
</tr>
<tr>
<td>RB2 (*)</td>
<td>A7 = 0.9862522</td>
<td>A7’ = 0.9862522</td>
</tr>
<tr>
<td>Motor of RB2 (*)</td>
<td>A8 = 0.9859224</td>
<td>A8’ = 0.9859224</td>
</tr>
<tr>
<td>PLC - motor of RB2 connection (*)</td>
<td>A7-9 = 0.998756</td>
<td>A9’ = 0.9845352</td>
</tr>
<tr>
<td>TT3 (***)</td>
<td>A10 = 0.9875664</td>
<td>A10’ = 0.9875664</td>
</tr>
<tr>
<td>PLC – TT3 connection (***)</td>
<td>A10-11 = 0.997413</td>
<td>A11’ = 0.9873243</td>
</tr>
</tbody>
</table>

Generally, in Table 3 A’ represents the availability of the scheme without redundancy, while A represents the availability of the scheme with redundancy. Elements denoted with (*) in Table 3 correspond to the first redundant
Because only for RB2 and TT3 and their connections we used redundancy (Figure 7), the values for A and A’ are different only for A7-A7’ to A11-A11’. The availability of the structure presented in Figure 7 was obtained using the following relations:

\[ A = A1 \cdot A2 \cdot \ldots \cdot A7 \cdot A9 \cdot A10 \cdot A11 \]  
(1)

and for the scheme from Figure 5:

\[ A' = A1' \cdot A2' \cdot \ldots \cdot A9' \cdot A10' \cdot A11' \]  
(2)

According to Table 3 the availability values are different only for the part of the scheme that use redundancy. Based on data values from Table 3 and relations (1) and (2) in Figure 9 a comparison between A (availability without redundancy) and A’ (availability with redundancy) is presented.

Figure 9: Availability with and without redundancy

It can be observed that availability increases when using redundant components. Redundant components can be used at any level (component, sub-system and system) thus improving global system availability.

The above-presented calculations were done at sub-system level (t3 control loop sub-system) but can be extrapolated at any level, including the system level.

CONCLUSIONS

The paper reveals the results obtained considering two distinct case studies for availability calculations for the t3 controlled sub-system component of the geothermal power plant control system.

During the calculation individual failure and repair rates were taken into account. The analyze was carried out based on availability schemes for t3 controlled sub-system with and without redundant components.

The results obtained conclude that redundant component usage significantly improves the availability of the sub-system.

Extending this analyze to the whole system (to all its sub-systems) provides a mode to increase the global availability by using redundant components in the main critical points of the system.

For several safety critical control systems the above analysis provide a very useful method to estimate system reliability/availability properties and reveals its critical points where redundancy may be used.

For these categories of control systems, it is essential to be able to guarantee their availability and safety functioning in all conditions.

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