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VHDL-AMS based genetic optimization of a fuzzy logic controller for automotive active suspension systems

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Outline

• Introduction and system model
• Shape optimization of fuzzy logic membership functions
• Integrated GA optimiser in VHDL-AMS testbench implemented as a state machine
• Experimental results
• Conclusion
Introduction and system model

- VHDL-AMS recommended by a European automotive consortium as a unified automotive modeling language
- Automotive active suspension system
  - Active suspension
  - Actuator controller

Fuzzy logic controller
Fuzzy logic controller (FLC)

- Based on the general principles of fuzzy set theory (L. Zadeh, 1965)
- Input and output variables are similar to a conventional controller
- Handling uncertain and complex systems, e.g. active suspension system
Fuzzy logic controller (FLC)

- Regular membership functions
  - Triangular
Fuzzy logic controller (FLC)

- Regular membership functions
  - Trapezoidal
Genetic algorithm (GA)

- Optimization method based on natural selection (D. Goldberg, 1989)
- A GA usually has the following elements
  - Population of chromosomes
  - Selection according to fitness
  - Crossover to produce new offspring
  - Random mutation of new offspring
Active suspension model

Sprung mass ($M_s$)

Unsprung mass ($M_{ul}$)

Controller

Actuator

Road displacement

$\ddot{x}_s$, $\dot{x}_s$

$F_a$

$B$

$K_s$

$K_u$

$x_s$

$x_{ul}$

$x_r$
Sprung and unsprung mass equations

\[ \ddot{x}_s M_s = K_s (x_u - x_s) + B (\dot{x}_u - \dot{x}_s) + F_a \]

\[ \ddot{x}_u M_u = -K_s (x_u - x_s) - B (\dot{x}_u - \dot{x}_s) + K_u (x_r - x_u) - F_a \]
FLC

- Inputs: sprung mass velocity and acceleration
- Output: actuator force
- Three linguistic variables: Positive (P), Zero (Z) and Negative (N)
- Fuzzy rules set
- Max-product inference
- Center of gravity defuzzification

<table>
<thead>
<tr>
<th>Velocity</th>
<th>P</th>
<th>Z</th>
<th>N</th>
<th>P</th>
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<tr>
<td>P</td>
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<td>Z</td>
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<td>N</td>
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Shape optimization of fuzzy logic membership functions

• **Fuzzy logic membership function**
  • Graphical representation of input’s degree of participation in a fuzzy set
  • Shapes may affect FLC performance (A. Barr and J. Ray, 1996)
  • Shape optimization using a GA
Shape optimization of fuzzy logic membership functions

GA Optimization
Integrated GA optimizer in VHDL-AMS testbench

- Integrated hardware system performance optimizer wholly implemented in VHDL-AMS
  - Active suspension system
  - FLC
  - GA optimization
Block diagram of one chromosome (VHDL-AMS entity)
Flow chart of a parallel GA
GA features:

- Evaluation – using peak-to-peak value of $x_s(t)$ as fitness
- Tournament selection – chromosomes with small $x_{pp}$ are more likely to be selected to produce offspring
- Elitism – artificially inserting the best solution into each new generation
- Arithmetic crossover – generate new offspring for real number genes
- Gene mutation – introduce new solutions into the next population

• VHDL-AMS finite state machine controls the optimizer
Experimental results

- GA optimized membership functions with irregular shapes
  - Velocity

![Graph of membership functions with irregular shapes](image-url)
Experimental results

- GA optimized membership functions with irregular shapes
  - Acceleration

![Graph showing the degree of membership for different acceleration values.](attachment:graph.png)
Simulation waveforms

System’s response to GA optimized FLC

Response to triangular membership FLC

Response to trapezoidal membership FLC

Time (s)
# Peak-to-peak and RMS values of $x_s(t)$

<table>
<thead>
<tr>
<th>FLC types</th>
<th>Peak-to-peak (mm)</th>
<th>RMS (mm)</th>
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</thead>
<tbody>
<tr>
<td>GA optimized</td>
<td>28.0</td>
<td>4.6</td>
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<tr>
<td>Triangular</td>
<td>35.7</td>
<td>6.2</td>
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<tr>
<td>Trapezoidal</td>
<td>36.0</td>
<td>6.4</td>
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Conclusion

- A novel way to improve FLC performance developed and successfully implemented in an HDL
- Novel approach to hardware performance optimisation proposed and implemented
  - Integrated VHDL-AMS optimiser using parallel GA
- New type of FLC with irregular membership functions proposed for automotive active suspension system
  - Superior performance to conventional FLCs with triangular or trapezoidal membership functions
  - More than 20% improvement in the peak-to-peak value of sprung mass displacement
Thank you!