Leso-Pb (Solar Energy & Building Physics Laboratory)

- EPFL (Federal Institute of Technology, Lausanne)
- ENAC (Faculty of Natural, Architectural & Built Environment)
- Address: LESO Building, CH-1015 Lausanne, Switzerland

- Head of the laboratory: Prof. Jean-Louis Scartezzini
- Integrated technology group: Dr. Nicolas Morel (e-mail: nicolas.morel@epfl.ch)

Teaching activities
- Lectures and "Integrated teaching units", architecture studios
- Continuous education (practioners, postgraduate courses)

Research activities
- Renewable energies, integration of photovoltaics
- Indoor air quality, air movements, passive cooling
- Daylighting, energy and colors
- Building and sustainable development
- Renovation
- Integrated technology, smart control of technical equipment
- Computer tools for research and building design
Research tools:
- Experimentation (real-size inhabited buildings, scale models)
- Theoretical models
- Computer simulation
- Software development

Sustainable development allows at the same time:
- to fulfill our needs
- while preserving the possibility for the next generations to fulfill their needs

Built on three basic principles:
- environment
- social
- economy
Buildings and Control Systems

- Significant impact on the energy consumption
  - decrease the energy consumption, while providing a similar prestation (i.e. user comfort: Tint, air quality, lighting level and quality, etc)

- Common issues:
  - solar gains are not taken correctly into account
  - artificial lighting is not controlled in a smart way
  - no blind controller, or blind controller not well designed
  - cooling device operation not well controlled
  - commissioning "forgotten"
  - no adaptation to user’s preferences
Control systems: Research projects at LESO

- DELTA
- Predictive Stochastic Control
- NEUROBAT
- EDIFICO
- Smart Window
- Sustainable Development LESO Building
- IEA SH&C Task 31
- AdControl
- Ecco-Build
- BELControl

Control Systems: Experimental Tools

The LESO building before renovation
Bio-inspired control systems, June 2006 – Slide 9

LESO building, outside view (during renovation, February 1999)

Bio-inspired control systems, June 2006 – Slide 10

LESO building, outside view (detail)
Inside view of an office room in the LESO building

Two windows in each room:
- lower window → normal window
- upper window → anidolic (non-imaging) daylighting system, window cannot be opened

Each window has its own blind (textile blind)
In each office room, following sensors and actuators are connected to the EIB bus:

**Sensors:**
- indoor air temperature
- illuminance level
- user presence
- window opening (switch)

**Actuators:**
- heating (on/off, pulse width modulation)
- blind position (window & anidolic blinds)
- artificial lighting (on/off + continuous dimming)

**User command buttons:**
- setpoint temperature
- blinds up/down
- artificial lighting (on/off + dimming)
Project AdControl: Goals

Basic goals of a (smart) lighting control:

◆ Optimize the user’s comfort inside the room

◆ Minimize the energy consumption used for providing comfortable conditions

Project AdControl: Requirements

◆ Priority of user’s wishes
◆ Minimize disturbances to user
◆ Adaptivity (to user’s wishes and to environmental conditions)
◆ Minimize energy consumption

◆ Integration with other control systems (HVAC)
◆ Use all available information from environment (sensors, user’s actions, etc)
Evolution of control systems

- Manual systems
- Automatic with simple algorithms
- "Intelligent" ("smart") algorithms
- "Intelligent" algorithms with adaptation to building characteristics and environmental conditions
- "Intelligent" algorithms with adaptation to user’s behaviour

Why adaptivity is important

- Adaptation to user’s wishes:
  - not all users are the same
  - a control system going against the user is rejected

- Adaptation to building characteristics and environmental conditions:
  - commissioning a control system is a demanding activity and a condition for a good operation
  - nevertheless, commissioning is very often "forgotten"
Structure of an adaptive control system

Mathematical tools

- Fuzzy logic (→ rule based control systems)
- Artificial neural networks (→ adaptive models)
- Genetic algorithms (→ adaptation of rules)
Fuzzy logic: an example

Membership function:

Fuzzy rule base:

<table>
<thead>
<tr>
<th>Ps</th>
<th>heating = negative</th>
<th>heating = zero</th>
<th>heating = positive</th>
</tr>
</thead>
<tbody>
<tr>
<td>season = winter</td>
<td>negative (*)</td>
<td>positive</td>
<td>positive_high</td>
</tr>
<tr>
<td>season = mid-season</td>
<td>negative</td>
<td>positive_low</td>
<td>positive</td>
</tr>
<tr>
<td>season = summer</td>
<td>negative</td>
<td>zero or negative</td>
<td>positive_low (*)</td>
</tr>
</tbody>
</table>

Genetic algorithms: a short overview

from Moshe Sipper, EPFL
Control optimization using GA's (1)

**Fuzzy parameters adapted through GAs:**
- Keep an energy efficient control
- Learn and integrate the user preferences

Expert control system for blinds, artificial lighting and heating devices

Users wishes

Control optimization using GA's (2)

» How the GA's are applied for the adaptation of a controller?

- an individual is a given controller, each gene being one parameter of the fuzzy logic rule

- fitness function = 1/\[energy consumption + discomfort level\]

- for an adaptation to user's wishes, the discomfort level is supposed to be zero when the user expresses a wish
Control optimization using GA's (3)

◆ Aims of the adaptation:
  – keeping an energy efficient control (→ CONTBASE, containing the current efficient controller)
  – adaptation and learning of the user preferences and behaviour (→ WISHBASE, containing all the wishes expressed by the user)

◆ Fitness function:

\[
\text{Fitness (c_i)} = \frac{1}{\sum_j (\alpha_j(c_i) - \alpha_j(\text{contbase}))^2 + 10 \sum_k (\alpha_k(c_i) - \alpha_k(\text{wishbase}))^2}
\]

Project AdControl: Computer setup

Structure of computer equipment and software used during the project AdControl
**Project AdControl: Experimental results**

<table>
<thead>
<tr>
<th>Controller type</th>
<th>Energy saving</th>
<th>Thermal comfort (satisfaction)</th>
<th>Visual comfort (satisfaction)</th>
<th>Rejection after 4 weeks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual</td>
<td>0 %</td>
<td>84 %</td>
<td>86 %</td>
<td>-</td>
</tr>
<tr>
<td>Smart, not adaptive</td>
<td>25 %</td>
<td>84 %</td>
<td>88 %</td>
<td>25 %</td>
</tr>
<tr>
<td>Smart, adaptive to user's preferences</td>
<td>24 %</td>
<td>86 %</td>
<td>89 %</td>
<td>5 %</td>
</tr>
</tbody>
</table>

Bio-inspired control systems, June 2006 – Slide 27

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**Project AdControl: Conclusions**

- Adaptation to user's wishes is an essential feature of an advanced control system for building services.

- If "intelligent" control systems allow a significant energy saving (up to 20 or 30 %), control systems adaptive to user's wishes allow to keep that number while increasing acceptance by users.

- Experimental results (measurements with real users) confirm the interest of the concept developed, based on GA's.
Ecco-Build: Partners

- Partners of the European research project Ecco-Build:
  - Fraunhofer Institute for Solar Energy Systems (D, coordinator)
  - Danish Building and Urban Research (DK)
  - Ingélux S.a.r.l. (F)
  - Swiss Federal Institute of Technology in Lausanne (CH)
  - Hüppe Form (D) (now Hüppelux)
  - TechnoTeam (D)
  - Bug-Alu Technic AG (A)
  - Servodan S/A (DK)
- Project duration: November 2002 - February 2006

Ecco-Build: Goals

- Develop a new generation of control devices for solar shading systems, glare control systems and electric lighting systems for the simultaneous optimisation of building energy consumption and comfort
- Develop glare criteria for windows and daylighting systems (used for control purposes)
### Ecco-Build: Work Packages

<table>
<thead>
<tr>
<th>No.</th>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Coordination</td>
<td>Develop new criteria for glare rating to be used as input for building management systems. The basis for the criteria are user acceptance studies in different countries.</td>
</tr>
<tr>
<td>2.</td>
<td>User assessment</td>
<td>Design and construct a device for luminance measurements. Characterise different facade systems.</td>
</tr>
<tr>
<td>3.</td>
<td>Measurement facility</td>
<td>Develop new control algorithms and construct a prototype controller.</td>
</tr>
<tr>
<td>4.</td>
<td>Control device</td>
<td>Develop an information package for building planners and scientific software tools to predict the energy impact of different control strategies for glare protection and solar shading devices.</td>
</tr>
<tr>
<td>5.</td>
<td>Design tool</td>
<td>Test the algorithms developed in WP4 in an occupied multiroom building and other pilot buildings.</td>
</tr>
<tr>
<td>6.</td>
<td>Experimental &amp; pilot buildings</td>
<td>Disseminate results to scientists, standardisation bodies, component and facade manufacturers, architects and building planners and set up a project Internet service.</td>
</tr>
<tr>
<td>7.</td>
<td>Dissemination</td>
<td></td>
</tr>
</tbody>
</table>

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### Ecco-Build: Control Device

- **WP leader:** LESO-PB/EPFL

- **Algorithm:**
  - start from the knowledge acquired during the preceding projects carried at LESO-PB/EPFL, especially the project AdControl (elaboration and experimental test of a user-adaptive control algorithm for fabric blinds, electric lighting and heating)
  - more complex shading systems considered in the ECCO-BUILD project (e.g. venetian blinds)
Ecco-Build: Control Algorithm

◆ Requirements:

– adaptive to user preferences  
  → should try to minimize the probability of rejection by user

– adaptive to building & environmental characteristics  
  → self-commissioning

– should allow the inclusion of angular characteristics of blinds

– should take into account both energy and visual comfort

Ecco-Build: Control Algorithm

◆ Variables to consider:

  – Control variables (Cᵢ)
    » \( f_e \) = fraction of electric lighting (0 to 1)
    » \( \alpha \) = opening fraction of blind (1 = blind retracted)
    » \( \beta \) = slat angle (0 = vertical/closed, 1 = horizontal)

  – Environmental variables (Eᵢ)
    » \( I_v, I_h \) [W/m²] or \( E_v, E_h \) [lux]
    » \( T_e, T_i \) [°C]
    » occupancy (0 or 1)
    » current time → solar angles

  – State variables (Xᵢ) determining the visual comfort
    » \( E_{h,wp} \) [lux]
    » \( L_{\text{window}} \) [cd/m²] or \( E_{v,\text{user sight}} \) [lux]
    » \( p \) = solar penetration depth [m]
Proposal:
- minimize a cost function
  \[ U = W_1 \cdot P + W_2 \cdot f_{th}(G) + W_3 \cdot f_{vis}(VDP) \]
  with
  - \( W_1, W_2, W_3 \) = weighting factors
  - \( P \) = power consumption of electric lighting
  - \( f_{th}(G) \) = function taking into account thermal effect of solar gains
  - \( f_{vis}(VDP) \) = function taking into account visual discomfort probability

- by finding the optimal values of control variables \( C_i \), under constraints \( 0 \leq C_i \leq 1 \)
Ecco-Build: Control Algorithm

The complete control system

Blind model:
- considered variants:
  » empirical model built by repeated measurements of environmental variables and control variables (look-up table)
  » blind model using daylight coefficients
  » blind model using bidirectional transmission distribution function (BTDF)
- adaptation typically once per day (for instance during the night, using all the measurements available)
- for the model using BTDF, the adaptation is easy because very few parameters (additional parameters characterising the window and the room) need to be adapted
Ecco-Build: Control Algorithm

Electric lighting model
- very simple model, for instance using a polynomial:
  \[ E_{el} = a \cdot f_{el} + b \cdot f_{el}^2 + c \cdot f_{el}^3 + d \cdot f_{el}^4 \]
- adaptation: by scanning several different values of \( f_{el} \) every night (when there is nobody) and a least square minimization

Bayesian model for Visual Discomfort Probability
- The controller should try to minimize the VDP = probability of rejection by user \( \rightarrow \) explicit probabilistic expression, using Bayes theorem:
  \[ P(A \mid B) = \frac{P(B \mid A) \cdot P(A)}{P(B)} \]
- In our case, the Bayes theorem can be used to express the probability of rejection R by the user, considering the conditions X (the expression can be easily extended to more than one variable X)
Ecco-Build: Control Algorithm

\[ P(R|X) = \frac{P(X|R) \cdot P(R)}{P(X|R) \cdot P(R) + P(X|\bar{R}) \cdot P(\bar{R})} \]

- In that expression:
  » P(R|X) is the probability of rejection for a given set of all the \( X \) variables, P(\( \bar{R}|X \)) the probability of acceptance
  » P(R) and P(\( \bar{R} \)) do not appear explicitly when calculating the derivatives, they can therefore be ignored (or just set to any reasonable number, such as 0.5 for both values)
- The only needed values remaining are the P(X|R) → can be extracted by "data mining", considering that:
  » the values just before an adjustment by the user are rejected values, giving P(X|R)
  » the values just after the adjustment are accepted values, giving P(X|\( \bar{R} \))

Ecco-Build: Conclusion

- **WP #2 (User Assessment)**
  - measurements with people were a little more difficult than anticipated → delayed
  - very interesting results, available from the responsible partners (ISE Freiburg and DBUR)
- **WP #4 (Control Device)**
  - delays of WP #2 and experimental setup also delayed WP #4
  - the general structure of the algorithm is well defined
  - prototype controller implemented using Java on a Linux PC
- **WP #6 (Experimental Test)**
  - started very late (end of 2005 at LESO-PB), with a lot of programming bugs and algorithm errors (too complex)
BELControl: Partners

- BELControl: Blind and Electric Lighting Control system

- Partners of the project:
  - LESO-PB, Swiss Federal Institute of Technology, Lausanne (coordinator)
  - Adhoco AG, Winterthur (industry partner)

- Project duration: August 2005 – July 2006

- Funding: CTI (only EPFL)

BELControl: Goals

- Complex control algorithm for blinds, electric lighting and heating (possibly also cooling and ventilation):
  - similar to AdControl
  - Genetic Algorithm to adapt to user preferences a fuzzy logic rule base
  - additional consideration for venetian blinds

- Elaboration, experimentation and realization of a commercial prototype

- Wireless sensors (Zigbee protocol)
BELControl: Work Packages

<table>
<thead>
<tr>
<th>1. Control algorithm development</th>
<th>1.1 Venetian blind control algorithm development</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.2 Integration of the new algorithm in the existing control algorithm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2. Experimental tests preparation</th>
<th>2.1 Implementation in the Adhoco technology (aHeart)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.2 Operational tests at LESO-PB/EPFL</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3. Field tests</th>
<th>3.1 Experimental tests at LESO-PB/EPFL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.2 Experimental tests in an inhabited residential one-family house</td>
</tr>
</tbody>
</table>

- **Deliverables:**
  - D1 = a new adaptive control algorithm for two blind types
  - D2 = implementation into a ready-to-use prototype
  - D3 = results of the experimental tests

- **Milestones:**
  - M1 = algorithm development done (D1) + start of experimental tests (12 months)
  - M2 = ready-to-juse prototype (D2) + experimental results (D3) available (24 months)

CCEM - Advanced Renovation

- **Tasks proposed by LESO:**
  - Investigate advanced control algorithm issues specific to renovation
    - Building not optimal on the viewpoint of building physics → special requirements for the control system
    - Difficult or impossible to use a building bus → wireless sensors
  - Complete developments on control algorithms
    - Venetian blinds and other complex shading systems
    - Rooms occupied by many users (e.g. open-space offices)
  - Elaborate a simulation tool as a final deliverable of the CCEM project, allowing to
    - Compare algorithm and implementation variants (energy, comfort)
    - Connect to traditional simulation tools (thermal, lighting, ventilation)