ENHANCED COMPUTATIONAL HVAC SIMULATIONS USING SOFTWARE AGENT TECHNOLOGY

Torsten Fahrig[1], Manfred Krafczyk[2], Bjørn Nachtwey[3] and Jonas Tölke[4]

ABSTRACT

In this paper we present HVAC simulations based on an interactive software prototype for fluid flow problems in civil engineering including optimization of an HVAC system by Computational Steering, high performance computing, efficient methods for model transfers (e.g. automatic grid generation) and high-level control functions for the design process.

With this prototype, engineers of different disciplines can locally or globally optimize the Predicted Mean Vote -index (PMV; Ritschel, 1994) by interactively moving objects and modifying parameters of the HVAC installation within a geometric modeling environment. Each modification of the geometry, the boundary conditions or the behavior of the HVAC installation will automatically trigger a recomputation of the index including three dimensional visualization. Additional the control loop of the HVAC system can be optimized by utilizing HVAC software agents.

In this paper we will validate the feasibility of our approach by simulating typical scenarios. Thus, the computational results of our prototype with its virtual measuring-, operation- and control- extensions will be compared with reference assets and field measurements found in the literature.

More specifically, the behavior of the global characteristic curve, which is defined by several coupled controlling elements (implemented as modules of the software agents), will be discussed. We describe the responsiveness of the HVAC Inlet agents to external measurements provided by additionally connected 'sensor' agents.

An example based on an initial variant of an HVAC installation in an office space highlights the practical use of an interactive optimization. The control engineer can modify parameters for the global characteristic of the control loop.

KEY WORDS

computational steering, software agents, interactive, virtual reality, real time, HVAC, measuring, operation and control engineering, IFC, AEC, product model, CAD, CFD, octree

---

[1] Research Assistant, CAB - Institute for Computer Applications in Civil Engineering - Technical University of Braunschweig, Phone: +49-531-391 7598, Fax: +49-531-391 7599, fahrig@cab.bau.tu-bs.de

[2] Professor, CAB - Institute for Computer Applications in Civil Engineering - Technical University of Braunschweig, Phone: +49-531-391 7590, Fax: +49-531-391 7599, kraft@cab.bau.tu-bs.de

[3] Research Assistant, CAB - Institute for Computer Applications in Civil Engineering - Technical University of Braunschweig, Phone: +49-531-391 7589, Fax: +49-531-391 7599, nachtwey@cab.bau.tu-bs.de

[4] Senior Research Assistant, CAB - Institute for Computer Applications in Civil Engineering - Technical University of Braunschweig, Phone: +49-531-391 7592, Fax: +49-531-391 7599, toelke@cab.bau.tu-bs.de

INTRODUCTION

Today common building simulation systems usually compute stationary states of HVAC systems with constant airflow rates of inlets. The dynamical behavior of HVAC installations depending on the climatic conditions inside a room which is controlled by measuring-, operation- and control- techniques cannot be modeled in such a framework. Yet, for a realistic modeling of HVAC engineering, such features are essential. To extend the present approach of HVAC simulation, we combine a Computational Steering approach and a software agent system.

In our prototype, these controllers are emulated by interactive software-agents, which are bidirectionally coupled with the simulation kernel and wrap the HVAC objects of the modeler. Software agent technology was chosen because of its ability to take corrective actions within a computational process during runtime.

GENERAL SYSTEM LAYOUT

The prototype is based on a geometric modeler, the CFD-kernel, a visualization toolset, HVAC agents and several interactive interfaces. In this paper we will focus on the implementation of the agent system. For details with regard to the other components we refer to (Fahrig et al., 2004).

The virtual design space and the HVAC functionality are provided in the modeler, which is based on the Autodesk Architectural Desktop (ADT; Autodesk). An extended IFC product model (Industry Foundation Classes; IAI) is serving as a general data basis which implements additionally all parameters for the prototype including the boundary conditions for the distributed CFD simulation kernel, the enhanced modeling functions and also the parameters for the software agents. All additional attributes are attached as an IfcPropertySet (IFC, IAI) to each geometrical object.

For the simulation process, product model specific data are being transformed into geometric objects (B-Rep model). The physical attributes of all objects and the global boundary conditions relevant for the CFD simulation is extracted and transferred automatically from the modeler to the pre-processor and finally to the CFD kernel (Tölke et al., 2003). The pre-processor, an octree based grid generator converts the data to a grid required by the CFD-kernel. The attributes of the facet model objects are adapted to the corresponding nodes of the CFD-grid (via a node-ID and an additional attribute list for each node-ID) and will trigger a consistent behavior in the CFD-kernel. The grid generator is optimized for grid resolutions used for computational steering simulation runs.

The simulation kernel is a research CFD prototype implementation based on a Lattice-Boltzmann approach (Tölke et al., 2003, Treeck et al., 2005). Parallelization is accelerated by asynchronous communication using non-blocking communication routines. For visualization the AVS environment (AVS/EXPRESS) is utilized. This software includes a powerful programming interface and many modules are available to expand its built-in library functions for visualization and communication with other software tools.

Even for large datasets AVS allows an efficient visualization of scalar and vector fields. Isosurfaces, isovolumes and streamlines are utilized to display the airflow and the distribution of the PMV-Index. The AVS environment is extended by VISIT (Visit, Jülich), a framework for computational steering optimized network communication and visualization. For better visualization quality the CAD geometry of the objects is imported directly to AVS as a triangulated surface (UCD file format). The data of the simulation kernel and the modeler are merged and scaled within AVS for consistent output.

Additional interfaces and communication systems are required for data exchange between the main modules. For the automated model data transfer, one way interfaces connect the main modules for modeling, computing and visualization. Bidirectional communication modules are required for the HVAC software agents to query sensor data and timing information. Their implementation is based on the TCP/IP socket communication protocol.

The virtual design space may externally be modified by additional engineers. This is possible by utilizing a multi-user-environment. Common software allows a remote sharing of PC desktop over the intranet or internet (VNC). Only one user at a time has control over the prototype via mouse and keyboard. In the meantime the other participants may monitor the modifications and their comfort related implications on the desktop screen or a Virtual Reality screen.

HVAC AGENTS

MEASURING, OPERATION AND CONTROL ENGINEERING

The following translation from recent literature (Recknagel et al., 2005) describes the purpose and the typical performance of control loops:

"An action controller has the task to keep the process variable x as precisely as possible at a predetermined, temporally constant or variable value and to reduce the influence of pertubations to a minimum. Another requirement is a stable behavior of the closed-loop control.

In addition, the action controller has to facilitate a rapid compensation of pertubations and adjustment to the set point. Furthermore, transient deviations of the controlled process variable (e.g. overshoots) have to be kept within certain limits. The completion of both requirements is not possible, so compromises have to be made."

In practice, expensive manual adjustments based on local measurements have to be made for every single control installation. This shows the enormous potential of computer aided control pre-optimization.

An typical control performance is depicted in Figure 1: overshoot is denoted by X_{max}, the approach time by T_{an} and the stabilization time by T_a. The tolerance band Δx can be chosen freely by the operator.

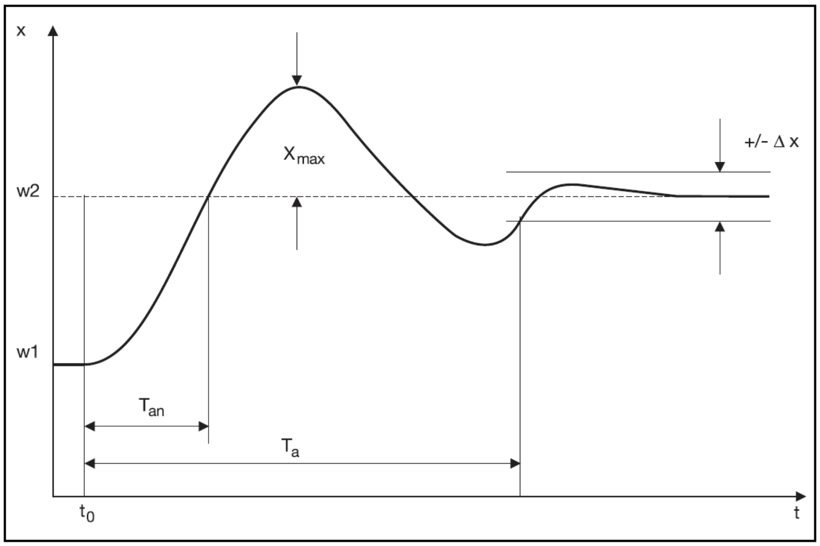

Figure 1: performance of control loops

According to (Schleicher et al., 2003) the most important tasks of a control engineer are:

- Determination of the process variables
- Evaluation of potential advantages offered by automatic control
- Determining the optimal position of measuring sensors
- Assessing pertubation intensities
- Selection of a manipulator
- Selection of a suitable controller
- Installation of the controller at reasonable positions
- Optimization by manual adjustment of parameters

The motivation of our project is a complete virtualization of these tasks for geometrical positioning and controlling by exploiting the capabilities of our prototype (especially 3D design space, CFD kernel, HVAC control agents).

GENERAL SOFTWARE AGENT SYSTEMS

Before starting with a detailed description of the HVAC agent system, we introduce the agent concept by quoting some concise definitions (Theiß et al., 2003):

"An agent is a system that tries to fulfill a set of goals in a complex, dynamic environment. An agent is situated in the environment: it can sense the environment through its sensors and act upon the environment using its actuators." (MIT)

"To summarize, agents are simply computer systems that are capable of autonomous action in some environment in order to meet their design objectives." (Wooldridge, 2002)

Comparing the principles of controllers for measuring-, operation- and control- engineering and the principles of software agents, we observe that an agent formalism is ideally suited to model the behavior of a set of controllers and sensors.

HVAC AGENT IMPLEMENTATION

To enforce a consistent simulation concept for HVAC measuring-, operation- and control-engineering the integration of software agents into the Autodesk Architectural Desktop is required in order to extend the interactive modeler to work as an automatic control system for the CFD kernel.

Two different types of HVAC agents exist in our system: An HVAC inlet agent who represents the air conditioning unit with all its attributes and regulation behaviors. The second type is the HVAC sensor agent. The "measured" data of a single or several sensors are periodically queried by the HVAC inlet agent. These agents represent individual geometric objects which can be moved and modified by the user like any other objects within the design space of the modeler.

Figure 2 shows a scheme with the main functions of the software agents. The sensor agent handles only a small set of data obtained from measuring local CFD data within the virtual room. After suitable intervals the sensor queries and receives comfort-relevant data like temperature and velocity directly from the simulation kernel via an integrated socket interface. Each newly generated sensor agent is appended to a list of one or more inlet agents which exist in the model.

The inlet agent controls the airflow stream and represents the air conditioning system including the controllers and their characteristics, the main component and the most complex element of the HVAC agents.

The controller compares the state of process variable in relation to its setpoint and produces the manipulating variable as a function of the measured deviation. The choice of a suitable controller specifically depends on its application. This holds for its mechanical features as well as its electrical characteristics.

There is a wide range of different designs of controllers and also manipulating devices (like pumps, valves, flaps, magnets, motor drives, ventilators). The combination and the arrangements of these single components define the general characteristic curve of the complete system.

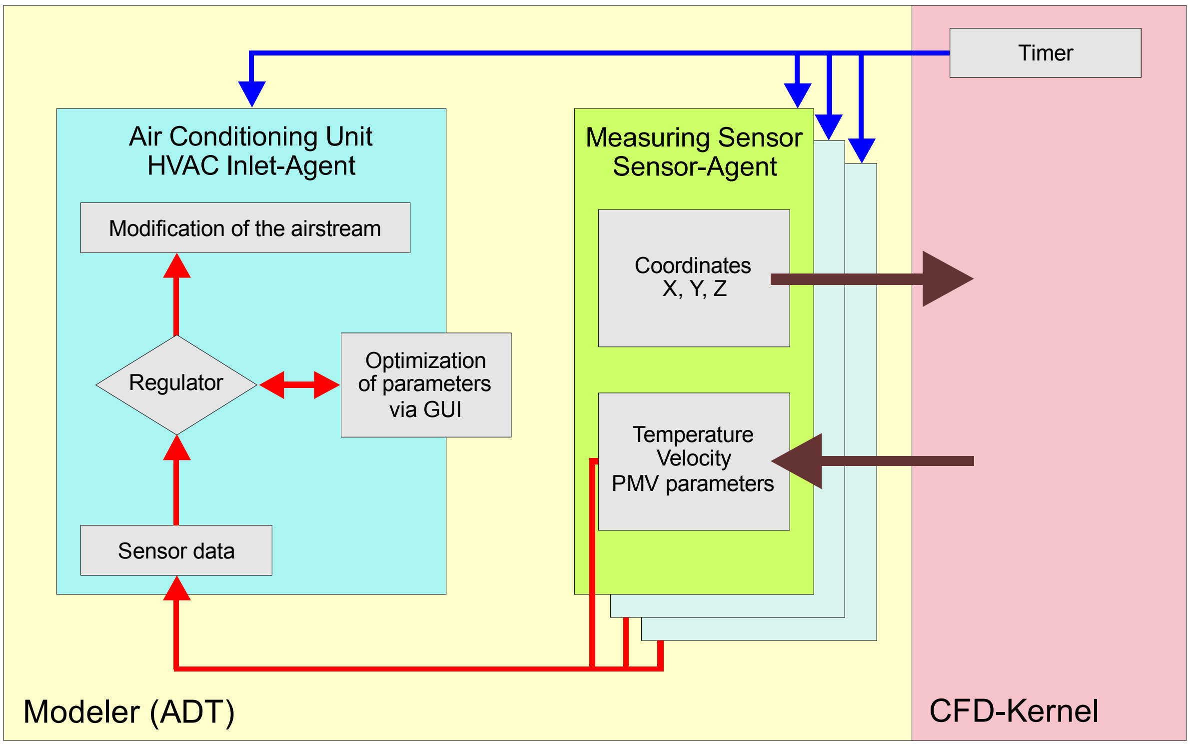

Figure 2: Scheme of HVAC agents

This characteristic can be mapped to agent modules acting as control elements. Their behavior is assembled by a combination of *P*roportional-, *D*erivate-, and *I*ntegral elements resulting in P-, I-, PD-, PI-, PID- controllers (Schleicher et al., 2003). Extended by additional parameters for self-limitation, dead lock time and timing elements they allow to describe the characteristic curves of most HVAC installations. Also PMV-index field diagrams can provide a basis for the regulation. All regulation parameters can be modified for each agent during runtime by a GUI (Graphical User Interface) within the modeler.

As all HVAC controlling and measuring processes are time-dependent, a timer is needed, providing a gauge signal for the agents. The timer is part of the simulation kernel and defines the global time scale.

The regulation controls the air flux of each HVAC inlet as a function of the air velocity, temperature and its deflection angle.

SIMULATION SCENARIOS

Several qualitatively different simulation and optimization scenarios can be realized within the described software agent framework:

In a first scenario we optimize the overshoot and the approach time of the global control loop by interactively modifying the parameters for the characteristic of the controller of the inlet. In case of a PMV-index field diagram defining the boundary conditions for regulation, the engineer can fit the dimensions of the field for an optimal cost-benefit ratio of energy consumption to PMV. The optimization is extended by combining the geometrical positioning of the HVAC installation (inlets, outlets and sensors) into the process.

In a different scenario we take advantage of an automatic dimensioning of the heating and cooling capacities of the inlets. Here, the room layout and heat sources (people, electrical devices, light sources) are considered. Parameters for the worst case state and the ventilation requirements are defined and transferred to a software agent. These parameters contain the maximum expected room temperature as a starting condition for the simulation, the stipulated temperature and the maximum evolution time, the whole room or defined areas (like the workplace) which have to be climatically adjusted. The agent starts a fully automated simulation batch run starting with a minimum of air cooling and low inflow velocities.

If the stipulated temperature is not reached in the specified time, the agent will automatically start a new simulation run with progressively increased air cooling, followed by increased air flux. The batch run is automatically finished if the desired HVAC performance is obtained during the predefined time interval.

SIMULATION

In the following section we sketch the simulation layout and compare the simulation results of a computational run of the agent-controlled prototype with results from the literature.

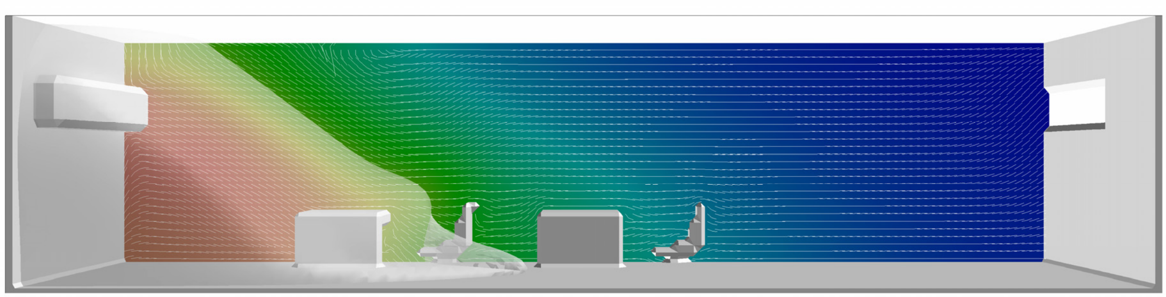

Figure 3: Office with agent-controlled HVAC inlet as simulation layout

Figure 3 shows a simple office space with an HVAC inlet as a wall-installation on the left side, an outlet on the right wall and some furniture. On the left table a virtual measuring sensor for temperature data is placed.

The sensor and the inlet are modeled by HVAC agents. The behavior of the inlet is defined by the inflow temperature as well as flux magnitude and direction. These quantities are regulated by I-controllers with a linear behavior and zero dead time. The temperature values are limited to a minimum of 18°C and a maximum of 30°C, the maximum air velocity is 0.35 m/s. The jet direction control emulates common HVAC inlet fins. The angle of these fins depends on the difference of the inflow air temperature and the room temperature.

In case of a high deviation of $\Delta T \geq 6°$ Kelvin, the air will be injected towards the floor with an angle of 5°, in case of marginal deviation, an air injection of 175° towards the ceiling is enforced. In intermediate states the angle is continuously adjusted with a linear behavior from 5° to 175°. (Recknagel, 2005).

The I-controller integrates the deviation signal applied to its input over a period of time. If the process variable is below the setpoint on an I-controller with a negative operation sense, it continually builds up its manipulating variable. When the process variable reaches the setpoint the manipulating variable may now be too large, because of the process inertance. The process variable is thus slightly increased; however, the manipulating variable is now reduced, because of the sign reversal of the process variable which is now above the setpoint.

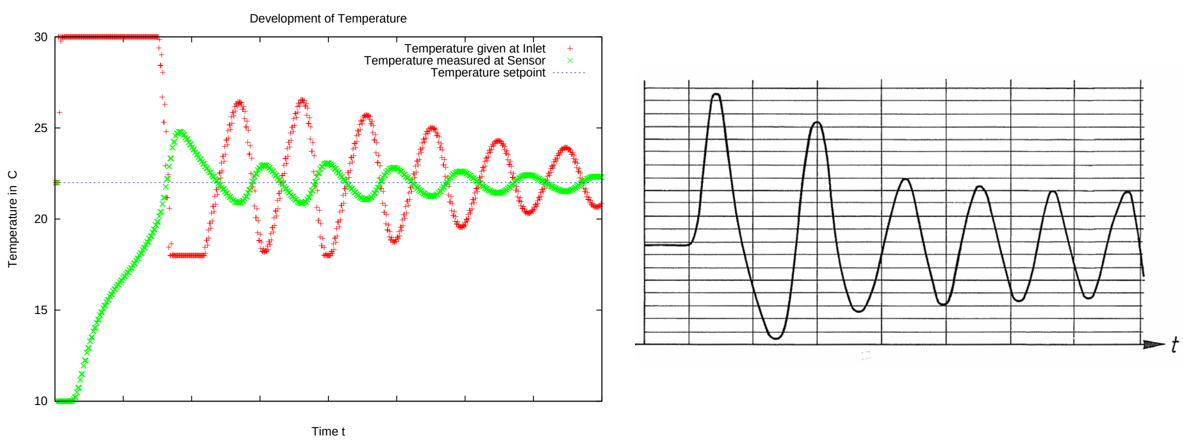

Figure 4: Behavior of an I-controller. Left: Results of simulation run with HVAC agents, Right: reference asset of the technical literature.

It is precisely this relationship that leads to a certain disadvantage of the I-controller: If the manipulating variable builds up too quickly, the effective control signal becomes too large, which results in an overshoot of the process variable. This cycle often results in a weakly damped oscillation of the I-controller based system.

For processes with long time scales, the I-component must be set very low, so that the process variable does not tend to oscillate. With this small I component, the I-controller looses its efficiency. For this reason, it is not particularly suitable for processes with long time constants like temperature control systems. Figure 4 shows the results of our simulation run (inlet temperature and measured temperature at the sensor) on the left side and a diagram showing field measurements of a reference asset from the technical literature (Bach et al., 1983) on the right side. Obviously both systems show the same qualitative behavior.

CONCLUSION

A prototype of a computational steering environment as the one described above can substantially reduce the time for many complex optimization processes which usually require substantial manual interaction in the course of the design process.

The integration of measuring, operation and control engineering extends the range of HVAC system simulations and improve their accuracy. The transient behavior of HVAC control loops can be studied and optimized in an intuitive manner. In combination with the computational steering features of the prototype, the control engineer has the possibility to "play" with the parameters which characterize the HVAC behavior. The presented simulation examples show that the approach is feasible for this field of application.

Computational dimensioning of an HVAC installation has a high potential for cost savings, because unlike with the majority of the available methods, one can for instance optimize specific regions of a room instead of the whole room. In this case, the required HVAC system may be dimensioned much smaller and thus cheaper.

The utilization of an object-oriented software agent system allows a simulation of a wide variety of problems in the area of control and regulation. Beside the interactive simulations, agents can also be used for simple batch automation as e.g. the dimensioning of an HVAC system or sensitivity analyses for which usually many simulation runs with expensive and iterative subsequent modifications of the parameters are required.

A reasonable improvement of the software agents would be an agent framework allowing an automatic analysis and modification of single control element features and manipulating devices stored in a component library for HVAC systems, because the control engineer is mostly interested in the manipulation and combination of every single component of the system (vents, sensors, fans, bowlers, pipes, cooling elements), secondarily on the modification of the global HVAC installation (full inlet) because it is of lower practical relevance.

REFERENCES

Autodesk Architectural Desktop / AutoCAD, http://www.autodesk.com

Autodesk Architectural Desktop - OMF Developer's Guide 3.3, Autodesk Developer Network, http://adn.autodesk.com

Autodesk ObjectARX Developer's Guide, Autodesk Developer Network, http://adn.autodesk.com

AVS/EXPRESS, http://www.avs.com

Bach, Baumgarth, Forsch, Reeker, Krinniger et. al. (1983), "*Regelungstechnik in der Versorgungstechnik*", Verlag C.F. Müller GmbH, Karlsruhe, Germany

Fahrig, Nachtwey, Geller, Tölke, Krafczyk (2004), "*A Product Model based Approach to Interactive CAE Design Optimization*" ICCCBE-X, Weimar, Germany

IFC / ifcXML, IAI – International Alliance for Interoperability, http://www.iai.org.uk

MIT Media Lab: http://agents.www.media.mit.edu/groups/agents/

Recknagel, Sprenger, Schramek (2005), "*Taschenbuch für Heizung und Klimatechnik 2005/2006*", 72. Auflage, Oldenbourg Industrieverlag München, Germany

Ritschel (1994), *Raumklimatechnik*, Band 1, Springer Verlag, Berlin, pp.125-153

Schleicher, Blasinger (2003) "*Control Engineering – A guide for beginners*", 3rd edition, JUMO Gmbh & Co. KG, Fulda, Germany

Theiß, Greb, 2003, "*Agenten im Bauwesen*", TU Darmstadt, Germany, http://www.agenten-im-bauwesen.net/

Tölke, Fahrig, Nachtwey, Krafczyk (2003): "*Computational Steering in Civil Engineering*", IKM - Internationales Kolloquium über Anwendungen der Informatik und Mathematik in Architektur und Bauwesen Weimar, Germany

Treeck, Rank, Krafczyk, Tölke, Nachtwey (2005), "*Extension of a hybrid thermal LBE scheme for Large-Eddy simulations of turbulent convective flows*", accepted for publication in Computers and Fluids

Visit at FZ Jülich, http://www.fz-juelich.de/zam/visit

VNC Software by RealVNC, http://www.realvnc.com

Wooldridge (2002), "*Intelligent Agents: The Key Concepts*", Lecture Notes in Computer Science , Volume 2322 / 2002, Springer-Verlag GmbH