MORE ELECTRICAL ENVIRONMENTAL CONTROL SYSTEM SIMULATION

Staack I*, Ellström H, Bergman M**, Sarwe P**, Krus P***
***Linköping University, 58183 Linköping, Sweden**
*******Saab Aeronautics***, SE-581 88 Linköping, Sweden**
ingo.staack@liu.se

Keywords*: environmental control system, scalable model, sensitivity analysis*

Abstract

This paper describes the development of a scalable simulation model of a bleed-less, fully electric Environmental Control System (ECS). The focus during development of the model was on fast execution speed and system architecture in order to enable optimization algorithms for system efficiency optimization to be constructed. Classical sensitivity and robustness analysis were used during model development. ECS architecture functionality and reliability has been proven for different flight mission working conditions as well as different failure modes. For this purpose, an analysis tool related to the simulation model and active simulation model control was developed.

1 Introduction

Alongside research on new aircraft layouts, optimized mission profiles, and the introduction of new materials in the aviation industry to produce more efficient and environmentally friendly aircraft, the focus is shifting more and more towards system level. The main key driver is propulsion technology with new, more efficient engine concepts which require a combination of well-adapted electrical sub-systems. The main power-demanding sub-systems are the environmental control system (ECS) or the anti-ice system.

But not only efficiency reasons but also enhanced comfort requirements as well as new cooling demands–the later especially in military aircraft–drive research on new ECS architectures [1].

Taking the step towards bleed air less, electrically-based aircraft implies and facilitates totally new system layouts of the ventilation and cooling system than used today. The key drivers behind a future Environmental Control System (ECS) are:

- (direct) power consumption
- system weight
- reliability and maintenance
- drag contribution / amount of ram air.

Nowadays, ECS studies, such as in the European More Open Electrical Technologies (MOET) project [4], are based on electric compressors and the inclusion of a vapor cycle to transfer the temperature level for low temperature consumers like air recirculation from the cabin [5]. The first civil example of such modern electric, bleed-less ECS is the Boeing 787-8 [2], although a compressor-driven and vapor cycle integrated ECS had already been used in the Douglas DC-8 but with bleed air driven compressors instead [3].

In this paper, both development and analysis of an electrically driven ECS are described. However, although most principles in this paper are valid for both civil and military aircraft, all statements and examples in this paper are related to civil transportation aircraft only. Sizing and estimation of the heat sinks and source are calculated on a virtual short/medium range, single-aisle aircraft similar to the A-320/B-737.

1.1 Limitations

In this paper, research on all electrical ECS is focused on power efficiency system architecture and system simulation. Other factors that drive design in reality include:

- weight and installation location
- reliability
- maintenance
- overall system efficiency (on total aircraft level).

These topics are only secondarily considered here or in the case of maintenance totally ignored. The reason for the absence of a quantitative comparison with a conventional ECS system is the problem of finding the right benchmarking or, in the case of an optimization comparison, penalty factors regarding:

- engine bleed air efficiency depending on engine operating state (shaft power versus bleed power)
- drag (or price equivalent) contribution of (additional) ram air channels
- weight penalty factor (in consideration against free component placement option).

In particular, the ram air channel drag contribution is a delicate problem, related to a large extent to the specific integration drag contribution. [6] shows that the topic of ram air channel against heat exchanger (HEX) size and arrangement alone is a very complex optimization problem. Other possible components that might help to enhance overall system efficiency, such as liquid skin heat exchangers (LSHX) or phase shifting material heat sinks are also beyond the scope of this paper.

2 Electric ECS Layout and Function

The main challenges in ECS design development are the wide operation range in pressure and temperature (ground hot case, cruise level cold case) as well as the balancing of different temperature levels of the consumers in an efficient manner.

In normal conditions, the main task of an ECS–both military and civil–is to cool down the aircraft. Within the aircraft, different thermal heat sources with different temperature levels can be found. These are:

- cabin, flight deck and event, cargo bay
- liquid loop cooled electronic devices
- air cooled electronic devices (especially avionic)
- additional air/liquid or liquid/liquid heat exchanger, e.g. for fuel and (engine) oil cooling.

The main drawback of the conventional ECS layout is the power loss from the bleed air pressure regulation towards the required cabin inlet pressure. The bleed air pressure cannot be actively regulated by the ECS; it depends mainly on the engine operating state and number/location of bleed ports in the engine compressor. This bleed air has been replaced by (stepless) controllable electric compressors in order to enhance ECS efficiency. Additionally, in order to raise temperature level of the outgoing fresh air from the pack, a vapor cycle has been added, which cools the cabin recirculation air.

Table 1 gives a brief overview and comparison of a conventional and the investigated fully electrical ECS:

	electric ECS	conventional bleed air ECS
fresh air supply	electric radial compressor (MC) and electric compressor-turbine (MCT) units; stepless controllable flow/pressure	self-driven compressor-turbine unit (pack); 2 to 3 bleed air off takes
recirculation cooling	via VCS; the VCS cooled by additional ram air channel together with liquid-cooled power electronics	non-existent
power electronic cooling	liquid/air HEX in outgoing cabin air	non-existent

Table 1: Main differences between conventional ECS and electrically driven ECS with VCS included

3 Simulation Model Development

The physical model is implemented in Modelica using the Dymola simulation program [7] in combination with an in-house developed component library.

3.1 Component/Library modeling

In order to fulfill the above mentioned demands regarding flexibility and simulation performance, a in-house developed moist air and liquid cooling fluids library developed was used. This library makes use of flow and volume dominated components, also named C- and Q-component style. A similar approach has already been used successfully to simulate fuel systems [8].

This air library, taking humidity phenomena like condensation into account, is lighter implemented and faster at runtime than most comparable libraries on the market. However, physical effects like enthalpy, pressure level and compressibility effects are implemented physically correctly by fluid-dynamic and thermodynamic physics laws, but mixing effects within volumes or multi-ports are ignored. In this case, a resulting global state for the component is calculated by simple mathematical average calculation, which limits the model to mixing and detail (cabin) flow modeling within a component.

Element type	Flow Components	Volume Components
Inputs	→ **pressure [Pa]**	→ **mass flow [kg]**
	→ spec. enthalpy [J]	→ spec. enthalpy [J]
	→ steam ratio [-]	→ steam ratio [--]
	→ free water ratio [-]	→ free water ratio [-]
Out-puts	← **mass flow [kg]**	← **pressure [Pa]**
	← spec. enthalpy [J]	← spec. enthalpy [J]
	← steam ratio [--]	← steam ratio [-]
	← free water ratio [-]	← free water ratio [-]

Table 2: Moist air port definition

This limitation is especially suitable for rather small volumes and components that are dominated by one physical effect like compressors, turbines, water separators or (ideal assumed) manifolds, but also has its limitations regarding modeling an aircraft cabin. Fig. 1 shows the model representation of the fuselage, composed of heat-capacity volume elements with included heat sinks and sources connected by tubes.

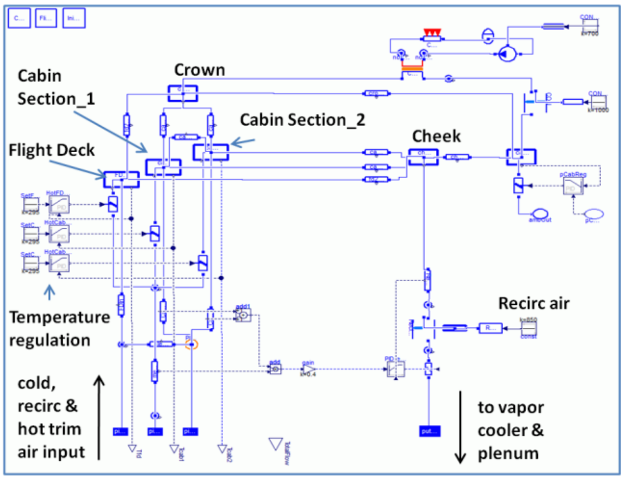

Fig. 1: Modelica cabin model with two passenger cabin sections composed of tube-linked volumes

A drawback of this "light" implementation is the high model stiffness, which requires a handy developer during model tuning in order to avoid unsolvable or enormously time-consuming start-point problems in the model; These problems, however, are often related to "wrong" physics, which means either undesirable–and in the model often not considered–backflows or oscillating phenomena on code branches in the Modelica code (called events), forcing the used flexible timestep solver DASSL (Differential-Algebraic System Solver) to solve the system matrix with infinitesimally small time steps.

Another–but not that hard–limitation is the connection limitation of the components by the already named "air port" definition shown in Table 2; defining them as either a flow component, calculating the mass flow based on pressure input and internal friction flow or as a volume port, calculating the resulting pressure depending on input mass flows. Temperature is not explicitly transmitted between components but can be calculated component-internally with the help of the spec. enthalpy, humidity and pressure.

3.2 Simulation Model Composition

The whole simulation model consists of the following three sub-components:

- aircraft fuselage model: flight deck, two cabin sections
- right and left pack module
- right and left VCS module

In order to handle flight mission conditions, environment air conditions, and coolant fluid definitions, additional global classes are added to the simulation model. This functional split-up allows both fast access to the different uncertainty parameter (mainly environmental parameter) and fast requirement-based case adaptations of both, operation conditions and used materials (e.g. coolant fluid).
Fig. 2 shows the (slightly simplified for better representation) simulation model pack architecture.

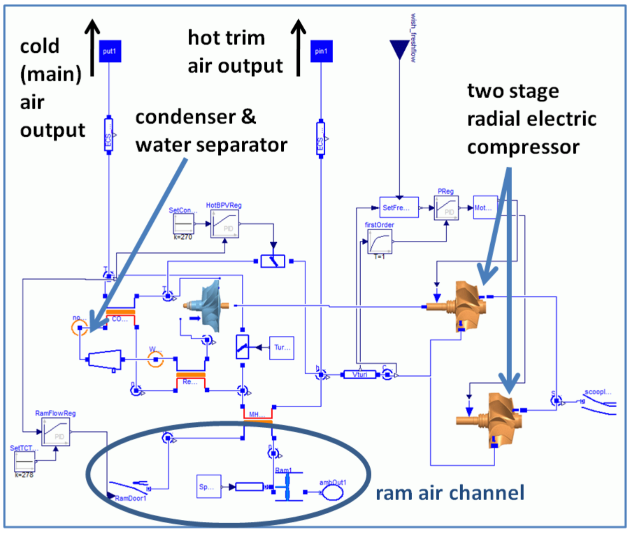

Fig. 2: Simulation pack model, simplified (reduced number of components and control system in favor of clarity)

3.3 Simulation Performance/Capability

Tests on a standard portable personal computer[1], simulating the whole ECS system over a flight mission resulted in a simulation performance approx. 300 times faster than real-time, depending on the state transitions in the flight mission. Fig. 3 shows a typical runtime over simulated time graph with the enormous amount of time taken to solve the start-value problem and slow execution progress during state variations such as climb at 4000 sec and descent at 9000 sec. Consecutive simulations in an optimization loop can be started with the last state result, avoiding the huge calculation effort at the start of a simulation.

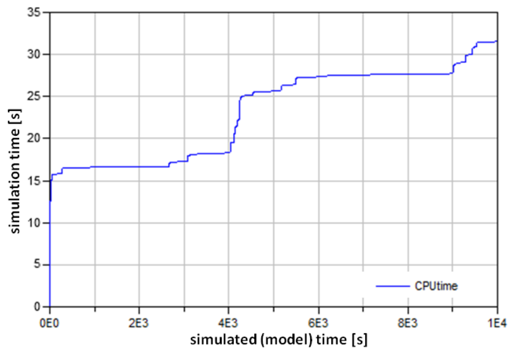

Fig. 3: Simulation speed over a civil flight mission

For better system separation, 3rd party cabin model testing, and runtime speed tests, a half-model was split into three Functional Mockup Units (FMU) [9]: half the fuselage, the central pack, and the VCS. These units were then reconnected in Dymola via the Functional Mockup Interface (FMI) and execution time was compared with the original all-in-one model.

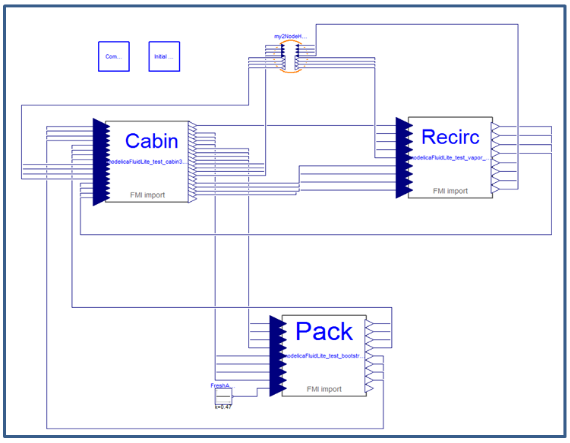

Fig. 4: FMU half-ECS-system model representation in Dymola

The resulting execution time was approx. six times slower than the original total system.

[1] Intel Core i5 M520, 2.4GHz CPU; 4 Gbyte RAM, Windows 7 / 64bit

Simulation speed has not been investigated further but in this case it might be related to the expanding numbers of ports due to the coupling of all the FMUs with the help of real parameters instead of the complex “air port” type in the original model. Fig. 4 shows the number of connections in a simplified half-aircraft-side model out of three FMUs representing (half the) fuselage, one ECS and one VCS.

4 Model Analysis and Benchmarking

As mentioned in relation to the limitations, system designs in aircraft are often limited due to high certification requirements regarding system reliability and safety. The ECS cools essential components and a malfunction might have major or catastrophic consequences; a total system malfunction during flight operation cannot be accepted. Fault analysis of the ECS, however, is not dealt with here, although a Functional Hazard Assessment was performed on the presented architecture.

Another main topic for a more electric aircraft is the amount of installed electrical performance, which–according to certification regulations– has to be as large as the maximum effect of all the consumers that might possibly connected at any one time. Consequently, system architecture, component sizing, and control scheme have to be analyzed together with the overall electrical power demand over the whole flight mission. For detailed system investigations, analysis, and case handling, two Matlab programs had been developed:

- SARA: **S**ensitivity **A**nd **R**obustness **A**nalysis
- TERESA: **T**otal **E**lectrical Pe**R**formance ande **E**nergy **S**ystem **A**nalysis

Both are object-oriented programs with Matlab class methodology [11]. Whereas SARA is primarily used during model development, tuning, and subsequent functional model analysis, TERESA is mainly used for system operation optimization taking into account the whole electrical system of the aircraft.

4.1 Sensitivity and Robustness Analysis

The sensitivity and robustness analysis tool “SARA” combines a complete Dymola result viewer, simulation model sensitivity and robustness analysis as well as a 3-D performance analysis tool applicable to generate surrogate models in a GUI.

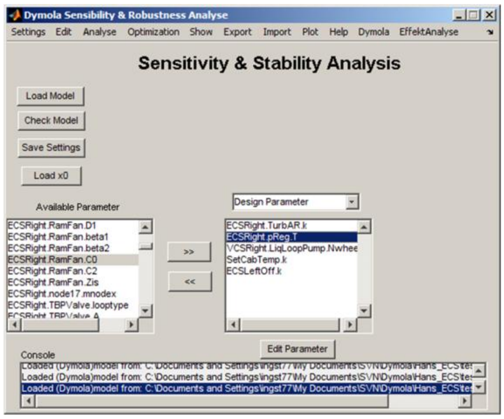

Fig. 5: Screenshot of SARA; definition of the sensitivity analysis parameter

Sensitivity analysis is the impact of design parameters on the system characteristics whereas the robustness analysis maps the uncertainty (often environmental parameters like e.g. ambient temperature) against the system characteristics. The model analysis is implemented according to [10] and is basically an alalysis of the derivative of the system at the investigated working condition(s).

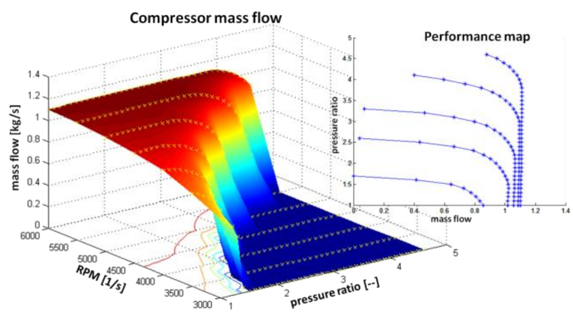

Fig. 6: Compressor performance analysis in the SARA tool

The program also contains a surrogate model or 3-D performance analysis tool, which is frequently used to track component behavior/efficiency over two input parameters. A classic example is compressor performance over rotational speed and pressure ratio; the analysis in SARA, shown in Fig. 6 is used for geometrical component sizing and working point adaption and helps the component developer verify component behavior.

4.2 Total Electric Power Analysis

The total electric power analysis tool TERESA makes a requirement case-specific power consumption analysis of the whole electrical system with specific focus on the ECS. It is used in order to calculate and visualize the total electric performance under different working conditions, called point performances. The main intension of this tool is to detect electrical power peaks and allow them to be reduced by changing components, system architecture or control scheme. To do so, three parts have to be considered:

- requirement handling and (automated) adaption/update of the simulation model
- performance point definition
- mapping of the electric system power parameters with the simulation model variables.

In this ECS related investigation, three different use case scenarios are defined by the requirements:

- hot condition with full passenger load
- normal (ISA) condition with full passenger load
- cold condition with minimum passenger load.

In addition to these three normal operation cases, the combinations with the main failure conditions single-pack operation and single-VCS operation have to be observed in the analysis. TERESA here manages the appropriate translation from the requirement /case definition to simulation parameter setup. This includes for example changing the mission definition according to reduced operational requirements, e.g. a lower cruise level (39,000 ft instead of 42,000 ft) in one-pack failure mode. Functional system characteristics values may also be lowered in one-pack operation, such as the amount of fresh air or allowed deviation of cabin temperature from the target value.

The investigated working points, called point performances are–as a result of the used mission definition–based on characteristic points of the flight envelope according to requirements or user selection (see Fig. 7).

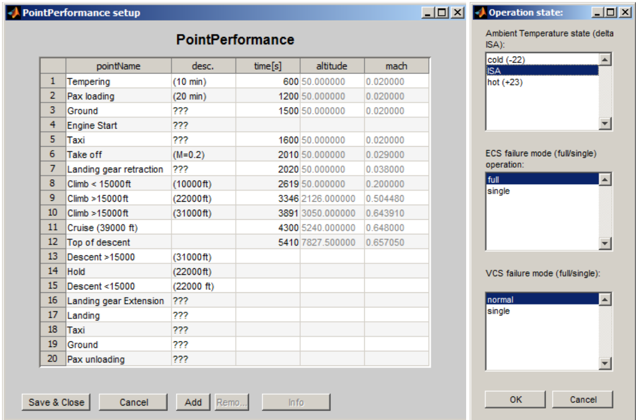

Fig. 7: Point performance definition (left) and requirement state handling GUI (right)

The central point, however, is the power table with the correlation between the power data, column-wise hierarchically sorted, and the defined point performances, represented line-wise (refer Fig. 8). The correlation can be defined by:

- predefined fixed (floating point) values, e.g. energy demand from systems not included in the simulation model Booleans, either predefined or retrieved from simulation results; mainly used for state information feedback
- simulation results: mapping of variable(s) and mathematic combinations of simulation result parameter; mainly used for direct model energy consumption read-out
- Cross-mapping between power parameters.

These project-related setup definitions are backed by a GUI, which helps the operator, e.g. by means of list boxes in the case of the simulation result parameters or a simple equation parser. This parser enables the user to define mathematical assignments, including simulation (result) parameter names as well as other power parameter (column) names.

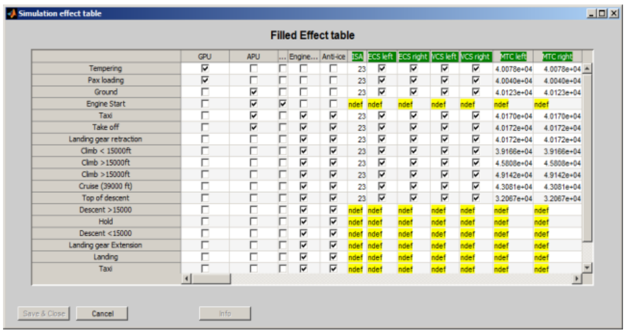

Fig. 8: Part of the effect table with simulation results (highlighted green) and undefined point performance states (highlighted yellow)

This described setup generally has to be done once a project is defined and can afterwards be saved together with the simulation model and the simulation results files. Furthermore, for documentation reasons and further work, a full export capability to Excel is implemented. The general default setup enables an adaption of the system also to other applications than the ECS system. Fig. 9 shows the definition of a point-performance condition and power parameter definitions with help of a Matlab fuction file.

This tool allows engineers unfamiliar with (Modelica) modeling to actively use a simulation model, e.g. provided by a college or other 3rd party, to work and analyze complex systems in Matlab (and Excel). It still, however, requires a Dymola license on the computer used to execute Dymola in the background.

```
%% T O T A L   E F F E K T   A N A L Y S   S E T U P   F I L E
%Automated generated setup file from xxeffektanalyse.makeSkript
%date: 22-Jun-2012 15:39:51

function myeff = projectSetupSkript()

  myeff = xxeffektanalyse();  %Make "clean sheet" project:
  myeff.effectClearAll();     %comment this line in order to get the default ECS
                              %analysis system setup

  %% POWER/ENERGY DEMAND SETUP
  myeff.effectAddParameter('Example effect');
  myeff.effectSetdata('Example effect',[1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1]);
        myeff.effectSetDescription(['This is an example how to define '...
                                    'a (predefined) effect parameter']);
  myeff.effectAddParameter('ECS left on');
        myeff.setFormula('ECS left on', 'logical(~dym("ECSLeftOff.k"))');
        myeff.effectSetDescription(['This is an example how to define '...
                                'a boolean value from a floating point '...
                                'variable from the connected simulation']);

  %% POINT PERFORMANCE SETUP
  myeff.pointPerfNames = [];
        myeff.addPointPerformance([],'Tempering','(10 min)',600,50,0.02);
end % projectSetupSkript
```

Fig. 9: Code snippet of the TERESA scripting project definition

5 Summary

A light humid air Modelica library with size-scalable components was used to simulate an electrically based ECS in a midrange civil passenger aircraft.

The simulation model, taking into account all significant heat sources and sinks, including the whole aircraft fuselage model, can be executed approx. 300 times faster than in real time over a standard civil mission on a standard personal computer. This fast execution time enables simulation-based optimization approaches but with the disadvantage of model stiffness. Handling all the model (design) parameters during sizing and component trimming required additional analysis tools like the described SARA and TERESA tools. With these tools, both classic sensitivity and robustness analysis and 3-D efficiency diagrams were performed. With the TERESA tool, simple requirement handling was added with active simulation model adaption to investigate system operation behavior and power consumption. Basic system optimization has been performed on load balancing between the pack and the VCS.

Limitation towards an overall system optimization–only from the efficiency view–is the complex correlation of HEX size, ram air channel(s) and the HEX arrangement in the air channel(s). Model architecture modifying functionality should therefore be added to the SARA/TERESA tools in future. Furthermore, both weight estimation and an engine power outtake efficiency model should be added to the optimization algorithm.

Acknowledgment

This work was financed by VINNOVA, the Swedish Agency for Innovation Systems. The contributing authors wish to thank VINNOVA for this support.

References

[1] Warwick G. Model design: Demand for power, cooling in advanced fighters drives new approach to system engineering. Aviation Week & Space Technology, November7, 2011, pp71-72

[2] Sinnett M. 787 no-bleed systems: saving fuel and enhancing operational efficiencies. *AERO magazine QTR_04 | 07*, Boeing Company, 2007

[3] Hershfield A., Air conditioned comfort on the Douglas DC-8 jet transport, *SAE Technical Paper 580368*, 1958, doi:10.4271/580368.

[4] MOET. The more open electrical Technologies project. http://www.eurtd.com/moet/

[5] Mevenkamp C, Galzin G. Electrical environ-mental control system for a passenger aircraft application, *Proc Workshop on Aircraft System Technology*, Hamburg University of Technology, 2011.

[6] Pérez-Grande I, Leo T. Optimization of a commercial aircraft environmental control system. *Applied Thermal Engineering*, Vol. 22, pp 1885-1904

[7] Modelon AB. Dymola software, http://www.modelon.com/products/dymola/

[8] Ellström H, Steinkellner S. Modeling of pressurized fuel systems in military aircrafts, Proc Simulation of onboard systems, Royal Aeronautical Society, London, 2004.

[9] Modelisa: The functional mockup interface, http://www.modelisar.com/index.html

[10] Krus P, Computational tools for aircraft system analysis and optimization, *Proc 26th International Congress of the Aeronautical Sciences*, Anchorage, Alaska, USA, 2008

[11] MathWorks: Matlab object oriented programming. http://www.mathworks.se/help/techdoc/matlab_oop/ ug_intropage.html

Copyright Statement