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Ecopteron

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Imagine Cup 2008, Embedded Development
Final Report

Executive Summary

For many areas of the world, the model-based projections for future climate are raising serious concern. This is because the adverse impacts of global warming and related changes in interconnected systems jeopardize the pursuit of sustainable development. Since further warming is unavoidable and some consequences of climate change are likely to be adverse and serious, the United Nations and the European Union actively promote mitigation and adaptation to climate change reflected in the Millennium Development Goals declaration. However, there is still a considerable uncertainty in detailed understanding of the present situation of natural processes. Therefore, an **intelligent monitoring system is urgently needed** as the modern toolkit for assuring sustainable development of the environment.

Although there is a necessity to develop a systematic approach to achieve a sustainable environment, due to the global scale involved, actions are conducted locally mostly by developed countries in the smallest territorial units, such as communes. Each unit, according to the valid directives (i.e. the water directive), is obliged to monitor numerous environmental indicators, which change dynamically. For example, the quality and quantity of water in a region, crop health and changes in temperature distributions over a range of landscapes. Each indicator provides valuable information only if it is observed regularly, in certain periods of time, which is currently unavailable due to a lack of dedicated instrumentation.

As a response to the presented problem we introduce **Ecopteron** – the first easy to use, self-navigating, unmanned, small electric helicopter, controlled by an embedded system, **designed to monitor dynamic environmental processes**. Discussions with scientists from the Polish Academy of Sciences and our own study of unmanned aerial vehicles enabled us to envision **Ecopteron**, which allows for:

- **Screening and alarming the occurrence of pestilence or crop fungi** and replacing the obligatory spraying on very rare pest species or fungi with a symptomatic one.

- **Effective monitoring of dynamics in local water resources** enabling the foreseeing of draughts more effectively and building new retention ponds in the most appropriate locations.

- **Monitoring of a local spatial concentration of greenhouse gases** leading to detection of noxious areas and applying appropriate countermeasures.

- **Observing the distribution of local temperatures over various landscapes** allowing for climate-friendly landscape structures based on real models and simulations to be designed.

- **Patrolling camp-fire areas in forests during dry periods** and identifying potential forest fire sources.

The innovative approach to the steering and the flight control of the helicopter, for which a crucial module is an embedded system, will make this device really simple to operate. After defining the flight parameters and destination points (e.g. ponds and crop field areas) on the operator's laptop using the map-based application, **Ecopteron**, will autonomously take off, make a cruise, during which it will visit waypoints and capture photographs or measure temperature, land in a defined place and finally synchronize gathered data with the operator's Geographic Information System database. It does not require any special runway, can be set up in several minutes and, due to its compact size, can be transported in every car trunk.

Figure 1. Helicopter model

Ecopteron's beneficiaries are farmers, landscape architectures, environmentalists, meteorologists and forest services. The project addresses in an innovative way several key problems generally known as precise agriculture, landscape architecture, small water retention or climate engineering. Moreover, data gathered by the **Ecopteron** could lead to designing effective measures for mitigation and adaptation to climate change in rural areas and, subsequently, to a more **sustainable environment**.

According to BCC research (2007), global expenditures for remote sensing products for climate change studies will rise from 560 million $ in 2007 to nearly 700 million $ in 2012. It is an optimistic forecast for the business future of the **Ecopteron** project, which would be delivered to the market as a product and as a set of remote sensing services at a cost effective price.

Situational Analysis

Problem Analysis

Humankind is stuck with global warming for at least several decades into the future, independent of the climate mitigation policy. The reason for even stronger concern is the adverse change in water availability. Many of the already dry areas are projected to become even drier and the presently wet areas – even wetter [*Millennium Ecosystem Assessment*, IslandPress, London 2005].

A problem with an inadequate quantity of water is likely to affect not only arid areas but also those with semi-arid and temperate climates. In the Wielkopolska Province of Poland, water resources, that are scarce already, are likely to be reduced in the future, actively constraining sustainable development. Models unanimously project temperature rise (of the order of 3°C in this century, or even more), which will directly result in the increase of potential evapotranspiration. Additionally, reduction of precipitation during the vegetation period is projected by several models. That is – there will be less rain in spring and summer and larger volumes of available water will evaporate.

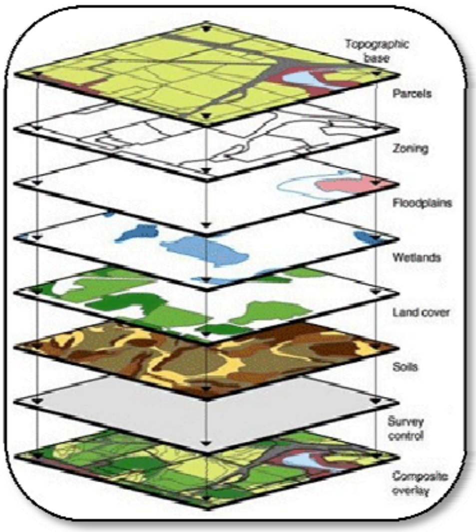

Figure 2. Geographic Information System overview

Since further warming is unavoidable and some consequences of climate change are likely to be adverse and serious, the European Union actively promotes mitigation and adaptation to climate change. Moreover, the United Nations declared Millennium Development Goals which define global areas of concern in terms of sustainable development and environment protection. However, there is a considerable uncertainty not only in projections for the future, but also in detailed understanding of the present situation of natural processes. The **intelligent monitoring system** would help us approach urgent problems of the environment, which accelerate the climate change, using quantitative measures.

Although there is a necessity to develop a systematic approach to achieve a sustainable environment, due to the global scale involved, actions are conducted locally mostly by developed countries in the smallest territorial units like communes. Each unit, according to the valid directives (i.e. the water directive), is obliged to monitor numerous environmental indicators, which change dynamically. For example, the quality and quantity of water in a region, crop health, changes in temperature in ecotone (transition area between two adjacent ecosystems) and greenhouse gasses emission. Each indicator provides valuable information only if it is observed regularly in certain periods of time, which is currently unavailable due to a lack of dedicated instrumentation.

Environmentalists nowadays estimate those indicators taking advantage of satellite images, aerial photographs taken from aircrafts or surveys done with the use of traditional statistical methods (extrapolating from data gathered manually based on a sample population). The biggest disadvantage of these methods are high costs, work consumption and lack of availability, which make them inappropriate for flexible and regular monitoring of the dynamic environmental processes at the local scale.

Remote sensing of the temperature, water storage, and water quality – the natural drivers of the climate change – would help us understand the functioning of a variety of landscapes. Better understanding of the local influence of the landscape structure on spatial and temporal distribution of temperature would be very important in designing effective measures for mitigation and adaptation to climate change in rural areas [*Climate Change*, IV Report IPCC, Cambridge University Press]

Undoubtedly, there is a necessity to follow Millennium Development Goals in terms of environment sustainability, which aim at improving the quality of life of humankind. However, the challenge is to turn those fragile and unfulfilled global commitments into real solutions. Since ancient times people have agreed that what cannot be measured, cannot be managed. Now this saying gains a new meaning in terms of **geoengineering**, which requires measuring each of the most important environmental indicators in order to create realistic simulations and find most appropriate local strategies of adaptation to climate change. That is why, without the effort to mobilize our powerful technologies, which are within reach, we will not succeed in finding a way to sustainable development. [Jeffrey D. Sachs, Earth Institute at Columbia University]

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Jeffrey D. Sachs

How the Ecopteron project takes aim at the sustainable environment in accordance with Millennium Development Goals?

[*United Nations Millennium Declaration, IV. Protecting our common environment*, New York, September 8th, 2000]

Millennium Development Goal	Action that should be undertaken	Expected impact on the environment	Question	
Stop the unsustainable exploitation of water resources by developing water management strategies at the regional, national and local levels	Maintaining the precipitation water in an area of its origin. Assessing local water storage and replacing melioration with small water retention-ponds according to local spatial dynamics in water resources. Small retention should be implemented by local governments in temperate climate lowland countries (IPCC, IV Report, Adaption practices).	Preserving existing ecosystems (both fauna & flora) what positively influences local microclimate. Increase in water availability for local farms during droughts.	**How to effectively monitor spatial dynamics in local water resources?**	
		Affects living conditions of ~30% of world population inhabiting temperate climate lowland countries.		
Intensify our collective efforts for the management, conservation and sustainable development of all types of forests	Periodically researching local spatial distribution of temperatures over various landscapes and modeling dependencies. Planning the most appropriate landscape structure for the region, including forests. Landscape architecture strategies should be implemented by local governments in semi-arid and temperate climate countries. (IPCC, IV Report, Climate drivers of change)	Mixed, mosaic rural landscapes, with shelterbelts, are likely to play a crucial role in adaptation to climate change, advantageously affecting conditions of energy and water balances, and partly compensating some adverse effects of climate change.	**How to observe spatial distribution of local temperatures over various landscapes?**	
		Affects living conditions of ~50% of world population inhabiting semi-arid and temperate climate countries.		
Embark on the required reduction in emissions of greenhouse gases	Monitoring spatial concentration of greenhouse gases in a region and finding most noxious areas. Applying a local mitigation strategy, by a territorial government, based on factual information about greenhouse gasses concentration.	Reduction of greenhouse effect. A key enabler of industrial and government action on climate change is the ability to accurately assess greenhouse gas emission.	**How to monitor a local spatial concentration of greenhouse gases?**	
		Global issue affecting every country around the world.		
Intensify cooperation to reduce the number and effects of natural and man-made disasters	Preventing forest fires caused by tourists' negligence by patrolling areas of potential camp-fires and early alarming (during dry periods). Nowadays aerial patrolling is limited due to high working costs of planes.	Reduction in number of forest fires. Higher potential fires detection rate.	**How to patrol camp-fire areas in forests during dry periods?**	
		15% of fires are caused by tourists' carelessness (IFFN No. 18)		
	Reduction of chemicals used in agriculture by introducing symptomatic integrated spraying against the very rare pest species and the crop fungi instead of obligatory spraying (requires regular monitoring of crop health status). Supporting the trend of 'precise agriculture'.	Preventing ecosystems from further contamination by pesticides and other non-biodegradable fertilizers. Reduction in costs of obligatory spraying for farmers.	**How to regularly screen and alarm the occurrence of pestilence or crop fungi?**	
		Affects all of the farmers (directly) and inhabitants (indirectly) in highly developed countries.		

Project Analysis

As a response to presented questions we introduce **Ecopteron** – the first easy to use, self-navigating, unmanned, small electric helicopter designed to monitor dynamic environmental processes. The use of a small, unmanned autonomous helicopter as a flexible remote multisensor, allowing for: monitoring water balance in a region, observing spatial temperature distribution over the range of landscapes, screening crop health status or measuring spatial distribution of greenhouse gases. As vital environmental indicators, this provides a completely new approach to monitoring environmental processes. It will provide us with a better understanding of the current condition of the environment, which is essential for developing appropriate regional policies, creating effective simulations of the environmental processes, and, last but not least, designing measures for mitigation and adaptation to climate change in rural areas in lowland, semi-arid or temperate climate countries.

Availability of sequences of aerial photographs of ponds, small rivers and meadows allows for the evaluation of current water quantity in the region and provides the specialists with the indications how to manage the small water retention in the region for the current season. The use of even the simplest thermovision camera capturing the infrared aerial pictures enables, for instance, to screen and flag up the occurrence of crop pestilence, which drastically increases the temperature of the sick plants (up to 9.0˚C) by limiting evapotranspiration. Infrared pictures are also very useful in assessment of water quality in ponds or lakes as well as in the observation of the temperature distribution over the range of landscapes. Taking advantage of gas sensors, it is possible to monitor the spatial concentration of greenhouse gases in a region. Apart from the long-term and regular monitoring, the data from **Ecopteron** can be used as a valuable support in the emergency cases, i.e. grasslands or forest fires and flooding, which harmfully influence the environment.

There are several conditions that should be met to assure safety of the flight of an unmanned auto-navigating helicopter, e.g. the wind strength at the maximum level of 3 Beaufort and relatively good weather conditions (excluding showers, storms or snowfalls). Moreover, **Ecopteron** cannot be used in inhabited areas (due to current flight policies) and during flight it must not exceed maximal allowed civil flight altitude for a given area. As **Ecopteron** uses an electric engine, the distance possible to cover without intermediate landing is limited to several tens of miles depending on the battery.

Figure 3. Aerial photographs of the crop fields

The prototype solution is based on an existing hardware model of a small electric helicopter, eBox-4300 and our own so ftware and electronics designed from scratch. The steering algorithms are developed and implemented completely by our team, based on the theory of avionics.

There are two general groups of potential beneficiaries of the **Ecopteron** project:

- **Direct** – i.e. operators – users of the Ecopteron's features.
- **Indirect** – beneficiaries of the services and applications based on the availability of the data gathered by the Ecopteron

Although both potential direct and indirect beneficiaries are listed in table below, our solution should be considered as a tool, possible to apply in numerous other cases requiring agile and flexible remote sensing of environmental processes. Taking advantage of an embedded operating system onboard, the solution is of a more generic type. It can be relatively easily extended by new algorithms interpreting data gathered by configurable and an interchangeable set of sensors, which makes the list of potential beneficiaries even longer and still open.

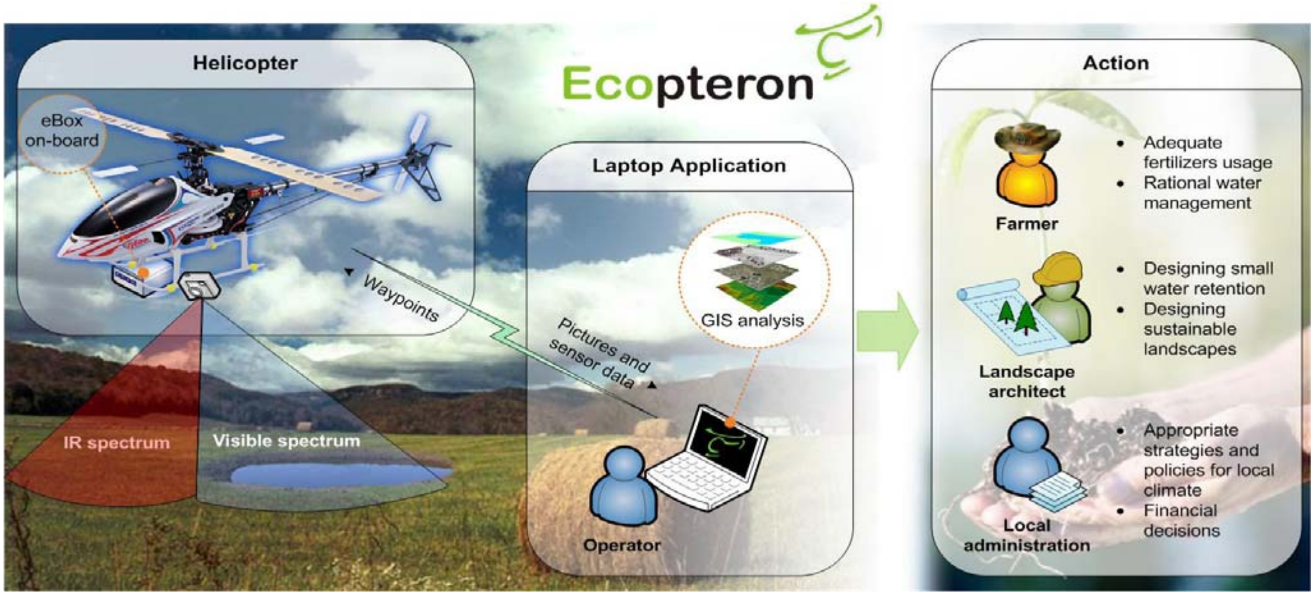
Agile monitoring of the environmental processes using the Ecopteron

	Question	Indicator	Remote sensing method	Application of gathered data	Beneficiaries
	How to effectively monitor spatial dynamics in local water resources?	Dynamic changes in the amount of water in ponds and small rivers, which can be easily observed	**Ecopteron** takes an infrared aerial photos of several ponds or small river periodically in the region (e.g. twice a week) Software measures a diameter of a pond or width of a river basing on an image recognition algorithm. Data are stored in GIS database.	**Foreseeing draughts** more effectively Building new retention ponds in most appropriate locations.	**Direct:** Environmentalists – easier and more time effective way of gathering data about local water storage **Indirect:** Farmers – timely preparing for potential draughts; saving money on irrigation due to availability of retained water;
	How to observe spatial distribution of local temperatures over various landscapes?	Spatial differences in ground and air temperatures in ecotones (e.g. borders between forests and crop fields)	**Ecopteron** monitors spatial temperatures in zones between forests and fields several times a day using a thermovision camera and temperature sensors. GIS software processes gathered data and models the influence of certain forest structure on a local microclimate.	Basing on real models in **designing most climate-friendly landscape structure**, e.g. mosaic and monocultural landscape or mixed landscape where fields are separated by woody shelterbelts and surface water bodies. **Possible decrease in local average temperatures by 1.0˚C.**	**Direct:** Meteorologists – easier, more effective gathering data about local spatial temperatures. **Indirect:** Farmers – better vegetation conditions, which result in potentially bigger harvest; Inhabitants – better living condition in more sustainable microclimate;
	How to monitor a local spatial concentration of greenhouse gases?	Spatial concentration of carbon dioxide, methane, nitrous oxide	**Ecopteron** monitors a concentration of greenhouse gasses using dedicated sensors in defined areas in certain periods of time and alarms if it detects above normal value.	Detecting noxious areas and applying appropriate countermeasures. **Area-oriented acting against greenhouse effect.**	**Direct:** Environmentalists – easier, more time- and cost-effective way of monitoring greenhouse gasses concentration **Indirect:** humankind (in general) – we are all posed to harmful effects of greenhouse effect.
	How to regularly screen and alarm the occurrence of pestilence or crop fungi?	Crop fields temperature	**Ecopteron** monitors crop field temperatures using a thermovision camera. Software analyses gathered data and alarms if it detects above normal differences in crop field temperatures' distribution.	**Alarming about the crop pestilence or fungi.** Applying symptomatic spraying on very rare pest species or fungi **Decrease in contamination level** of local water resources and soil.	**Direct:** Farmers – reduction in costs of obligatory spraying; precise information about crop health **Indirect:** Inhabitants – better living in less contaminated environment.
	How to patrol camp-fire areas in forests during dry periods?	Camp fires in prohibited areas	**Ecopteron** patrols potential locations of camp fires and detects fire using thermovision camera (only during high fire risk periods).	**Alarming about potential source of forest fire**, when it is not too late for counteraction.	**Direct:** Forest service – reduction in costs of aerial patrolling using traditional planes; more time effective and usable way of patrolling forest during dry periods. **Indirect:** Inhabitants of forested areas – safer living conditions due to lower risk of fire.

User Experience

The innovative approach to the steering and the flight control of the helicopter will make this device really simple to operate, even for a person without any experience in steering unmanned aircrafts. After defining the flight parameters (altitude, speed etc.) and destination points (e.g. ponds, crop field areas etc.) on the operator's laptop using the map-based application, **Ecopteron** will autonomously take off, make a cruise, during which it will visit waypoints and capture photographs or measure temperature, land in a defined place and finally synchronize gathered data with the operator's Geographic Information System database. It does not require any special runway, can be set up in several minutes and, due to its compact size, can be transported in every car trunk. The training required before using the **Ecopteron** would consist of three simple phases:

- Introduction to the flight planning using a laptop map-based application.
- Setting up the hardware before the take-off.
- Dealing with potential emergency situations.



Primary Usage Example

Periodically, an environment engineer goes out for a 'patrol' of his area to investigate the environment: water quality and quantity, crops condition, and general environmental indicators. He packs his laptop and the **Ecopteron**. Every ten kilometers he stops and launches the **Ecopteron**. On a laptop he configures waypoints that determine the path of flight. The onboard AI takes care of steering the helicopter and flying through given waypoints. During the flight above the fields, **Ecopteron** captures aerial photographs, tagging each one with GPS coordinates. These pictures are stored on the eBox USB high capacity flash memory. After landing, pictures are transferred to the laptop, processed and imported into GIS (Geographic Information System). After finishing the patrol, the engineer returns to his office and analyses all the gathered data. This way of systematic monitoring aids the understanding of natural processes which continuously happen around us. If any anomalies are detected, adequate actions can be undertaken.

Market Analysis

Ecopteron's viability in the marketplace should be considered in two aspects:

- **Ecopteron as a product**
  A company would provide potential customers with customizable products, i.e. **Ecopteron**s supplied with certain sensors and configured according to customers' needs. In this case the company should also offer introductory training and servicing during the guarantee period.
- **Ecopteron as a service**
  A company would provide potential customers with remote sensing services, e.g. crop health scanning, helping to develop expertise on the spatial temperature distribution over a range of landscapes or local water resources and water quality. Such services should also include consulting, data processing using GIS system, research and reporting.

Service	Competitors		Ecopteron's advantage
Crop health assessment	Experts in Agriculture using statistical methods	☑	Accuracy, time-effectiveness, covering larger areas
Monitoring of dynamics in local water storage and droughts forecasting	Sensor networks providers, Environmentalists using statistical methods, Aerial photos providers (using traditional planes)	☑	Availability and flexibility, time- and cost-effectiveness, better precision due to GIS processing and modeling
Monitoring of a spatial temperature distribution over the range of landscapes in the given region	Weather stations, Infrared satellite imagery	☑	Accuracy and agility, possibility to use during cloudy days
Monitoring of local spatial concentration of greenhouse gasses	Ground remote sensing services, Aerial remote sensing using traditional planes	☑	Accuracy, possibility to use in a hardly accessible areas, cost effectiveness
Patrolling forests during dry periods	Aerial patrolling using traditional planes or helicopters	☑	Drastic difference in working costs which increases availability of the service. Environment friendliness due to electric engine and silent work.

Table 1. **Market analysis**

The target of the **Ecopteron** project is divided into two groups:

- **Public:** landscape architects, meteorologists, fire brigades and environmentalists employed in local governments' environmental protection departments. Each group of beneficiaries has a budget to be spent on environmental processes monitoring and investing in new technologies. Taking into consideration **Ecopteron**'s advantages and cost effectiveness. It would certainly be an interesting offer for these potential customers in the public sector.
- **Private:** farmers or communes of farmers, which could minimize losses in their harvests by early detection of pestilence or crop fungi, saving money on unnecessary crop spraying. **Ecopteron** will let them make one step forward to environmentally friendly, precise agriculture, which is an objective of numerous grants and subsidies, e.g. EU subsidies.

The existence of other prototypes of UAVs in the market would not pose a threat to the interests of a company offering **Ecopteron** as a product or service. Currently, to our best knowledge, there are no similar solutions available allowing for agile monitoring of dynamic environmental processes. Existing UAVs most often aim either at military and intelligence or the energy sector.

Strengths	Weaknesses
☑ The first UAV enabling for agile monitoring of dynamic environmental processes ☑ Provides existing customers with an innovative, agile, cost- and time-effective remote sensing solution (tool and services) ☑ Introduces a new approach to quantitative measurement of environmental processes ☑ User friendliness – easy to use almost without training ☑ Self-navigation – taking advantage of the steering AI does not require on-line control ☑ Environment friendliness – electric powered, silent working. Useful also in natural protected areas ☑ Generic architecture and use of the embedded OS make it easily adaptable to customers' needs	☒ Lack of the strict target group increases marketing costs ☒ Cannot be applied in all weather conditions and in inhabited areas ☒ Indirect influence on the environment (**Ecopteron** provides comprehensive data, decisions still depend on local administrations and policies) ☒ **Ecopteron** is not a cheap solution ☒ Requires flight permit (in some countries)
Opportunities	**Threats**
☑ **Ecopteron** may be partially financed from grants, since it addresses serious real world problems on which time and money are spent, i.e. climate engineering, small water retention, forest fires, soil contamination etc. ☑ Possibility to discover new applications through cooperation with clients, which could result in a unique know-how	☒ Potential additional applications may require long-term and costly research ☒ Global companies conducting researches on UAVs.

Cost analysis

Helicopter equipment	
Helicopter model	$ 630
Gyro GY-401 + tail servo	$ 293
3x swashplate servos	$ 151
2x aditional Li-Polymer battery	$ 228
Charger + Li-Polymer balancer	$ 185
Total	$ 1487

Electronics	
eBox	$ 85
Electronics parts	$ 326
3D Compas	$ 233
Gyro 3D	$ 163
3x accelerometer 3D	$ 112
Gas sensors	$ 35
USB camera	$ 116
Total	$ 952

Variables	
Ecopteron sell price	$ 10 000
Service price	$ 700
User training cost	$ 500
Employee cost/year	$ 20 000
Average marketing costs/year	$ 20 000
Servicing costs/year per UAV	$ 300
Servicing price/year per UAV	$ 500
Max flights/year per UAV	100

Software & hardware development effort estimation based on FP & COCOMO

Function points (FP) calculation	
CM (complexity multiplier)	0,8
UT (unadjusted total)	290
IF (influence factors)	0,31
CM + IF	1,11
FP = UT x (CM + IF)	321,9

Software size estimation	
LOC / FP	60
LOC generated by SD tools	15%
Total LOC	16417

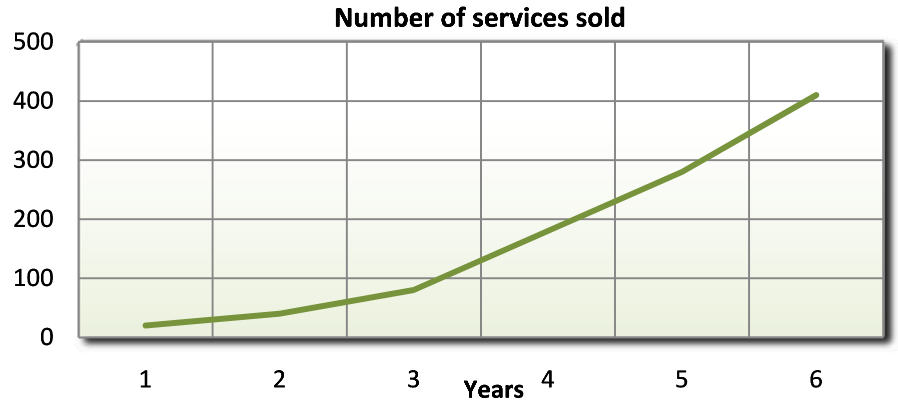
Effort estimation	P.months
Software (design & dev.)	32,8
Hardware (design & dev.)	10
Total PM	42,8

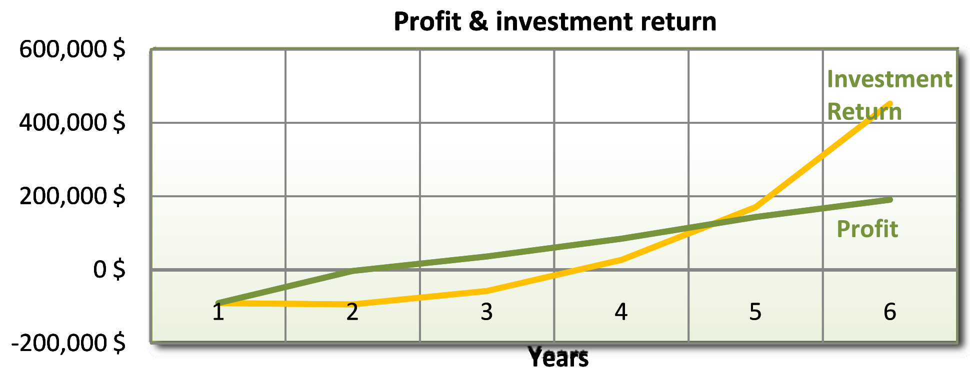
Cost estimation	
Total PM x monthly salary	$ 81 528
Prototype cost	$ 1500
Total cost	$ 83 028

Company starting costs	
Helli with flight equipment	$ 1 487
eBox with sensors	$ 952
Thermal Vision	$ 3 000
Software & Hardware design	$ 83 028

Business simulation

Year	1	2	3	4	5	6
Number of UAVs sold	1	1	2	2	3	3
Number of services sold	20	40	80	180	280	410
Number of used UAVs	1	1	1	2	3	5
Number of employes	1	1	1	2	3	5
Costs	$ 128 767	$ 42 739	$ 42 739	$ 65 477	$ 88 216	$ 133 693
Income	$ 25 000	$ 39 500	$ 79 000	$150 000	$ 232 000	$ 324 500
Profit	$ 103 767	$ 3 239	$ 36 261	$ 84 523	$ 143 784	$ 190 807
Investment return	$ 103 767	$ 107 005	$ 70 744	$ 13 779	$ 157 563	$ 452 137

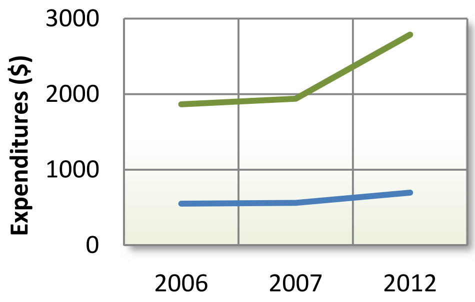




Market size

According to BCC research, over the past two decades, industry analysts have observed that many industries have begun to make use of what is generally referred to as geographic information systems (GIS) in their day-to-day operations. Remote sensing technology, such as **Ecopteron**, makes it possible to supply GIS databases with real data and use them on the scale greater than ever before. Latest projections state that in such a way a new competitive remote sensing industry has emerged [Remote Sensing Technologies and Global Markets, BCC Research 2007].

Global Expenditures for Remote Sensing Products, by Application, through 2012 *(BCC Research 2007)*				
Application	**2006**	**2007**	**2012**	**CAGR (2007-2012)**
Climate Change Studies	550$	560$	697$	4.5%
Other Applications	1,866$	1,940$	2,788$	7.5%



Research Description

Main goals of the **Ecopteron** project were identified throughout discussions and focus studies with scientists from the Polish Academy of Sciences (prof. Andrzej Kędziora, prof. Zbigniew Kundzewicz). They helped us realize the importance of flexible monitoring of the environment, and provided us with interesting and valuable references to the literature: Millennium Ecosystem Assessment, Global Development Goals Declaration and IPCC Report on Climate Change. The cooperation with scientists allowed us to find out the most discussed recent global environmental problems requiring innovative remote sensing, such as: climate friendly landscape architecture, remote sensing of water storage, precise greenhouse gasses emission evaluation, reducing soil contamination by unnecessary crop spraying or preventing forest fires caused by human negligence. Our own research on the possibility to use unmanned helicopter as a universal and agile remote sensor enabled us to specify innovative features of the **Ecopteron**.

We have analyzed several alternatives to unmanned helicopter as a remote sensing platform, but their drawbacks disqualified them from further consideration. Sensor networks, which are relatively easy to build are difficult in maintenance and become too expensive when they are used for covering larger areas. Satellite imagery's main drawback is its lack of usefulness during cloudy days, which happen often in temperate climate. Finally, unmanned planes require runways and much more open space than small unmanned helicopters, which makes them useless in woody areas.

To assess the market viability of the **Ecopteron** as a product or a service, we used the research conducted by BCC Research (Remote Sensing Technologies and Global Markets) and the Report on perspectives of the remote sensing market in Europe [C. Rousseau, V. Singhroy, Canada Centre for Remote Sensing, Ottawa].

Technical Analysis

Overall Architecture

Ecopteron system consists of three main modules:

- **Helicopter** – a small model of flying vehicle equipped with steering mechanisms.
- **Electronics** – designed from scratch flight control motherboard with a variety of sensors necessary for steering.
- **eBox-4300** – the 'brain' of the helicopter, controlled by our Windows CE embedded system and dedicated software.
- **Desktop application** – interface to command the helicopter.

Electronics

The sensors are **Ecopteron**'s eyes and ears. They can be divided into two groups:

- Core sensors, providing flight parameters necessary to steer the helicopter (listed in Table 1)
- Additional sensors, chosen accordingly to the assignment

Five microcontrollers collect data from these sensors. Most sensors communicate using a I2C serial bus, which is a well known and robust industry standard. Sensors with analog outputs are connected directly to A/D converters. Microcontrollers communicate with eBox using a RS-232 port. This interface is simple in implementation, and provides predictable timing, thus complies with hard real-time constraints.

As a form of a 'backdoor', we used hardware multiplexers between steering engines and microprocessors, which enable us to take over the steering using a standard Remote Controller in case of unpredicted situation during development and testing.

Core Sensors	Functional Sensors
Gyroscope	Camera
Accelerometer	Thermal vision*
Compass	Gas Sensors
Altimeter	
RPM meter	
GPS	

Table 2. Ecopteron's sensors.
* planned In future

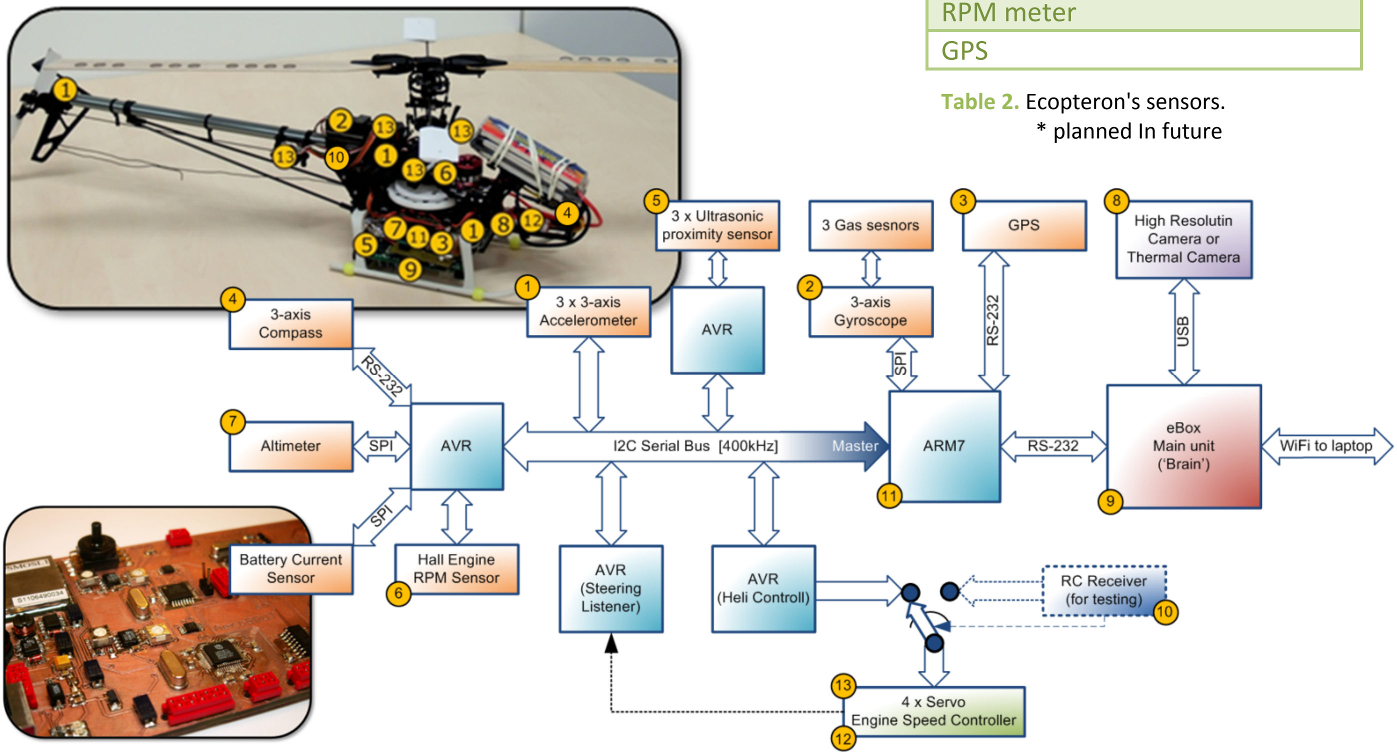


Figure 4. Electronics architecture and parts layout

eBox

The 'brain' of **Ecopteron** is eBox-4300 with a hard real-time operating system. Features of eBox-4300 make it ideal for such an application.

Small size, low weight and sensible power consumption enables embedding eBox in helicopter with minimal impact on flight length. To further reduce weight we removed the eBox case. In future, unnecessary subassemblies, i.e. the audio chipset, can also be detached.

The Windows CE real time operating system guarantees deterministic data processing time and timely steering commands.

eBox is equipped with a USB camera to observe the environment and take pictures when needed. Pictures are stored on a Compact Flash card. Additionally, a wireless module provides communication with laptop or a PC. During the flight it also serves testing purposes – to observe all sensors data.

Helicopter - Technical data

Our prototype helicopter (wing diameter 72cm) with eBox onboard has a weight of about 1kg – the helicopter with the battery weighs about 800g, the eBox without the case adds only 160g and an additional 20-30g is the weight of sensors. Currently we use 11,1V 2.2Ah batteries, allowing for about 15 minutes of continuous flight with a top speed up to 100 km/h at a maximum altitude of 400 meters. The final version would be equipped with 14.8V 6.0Ah batteries, extending flight length up to 1 hour. Optionally, the helicopter can be equipped with a thermal camera, which greatly extends

Model		Prototype	Final
Weight	Helicopter with battery	800	900
	eBox w/o case	160	160
	Electronics	30	30
	Total	990	1090
Batteries	Voltage	11,1V	14,8V
	Capacity	2,2Ah	6.0Ah
Maximum flight time		15min	1h
Maximum speed		100km/h	100km/h
Maximum altitude		150m	150m

Table 3. Helicopter models technical data

project functionality but triples the cost of the solution.

Laptop

The helicopter is an autonomous vehicle, but still it needs to be given orders. Defining its mission is the task of the laptop application. Before takeoff, the operator specifies the flight route by choosing waypoints on a terrain map presented by the laptop application. These waypoints are sent to helicopter. After landing, the helicopter sends gathered information directly to the laptop application, where the data can be presented and further processed.

Software Overview

In the **Ecopteron** Project we have developed software for three hardware platforms: microcontrollers, eBox-4300 and the PC computer.

Our helicopter has 5 microcontrollers on board. Each and every one of them is executing code written in C. Four of them are AVRs microcontrollers gathering data directly from sensors. Next, AVRs pass data to ARM7. This master microcontroller assembles data into 72 bytes length format and 100 times per second sends such a frame via RS232 to eBox.

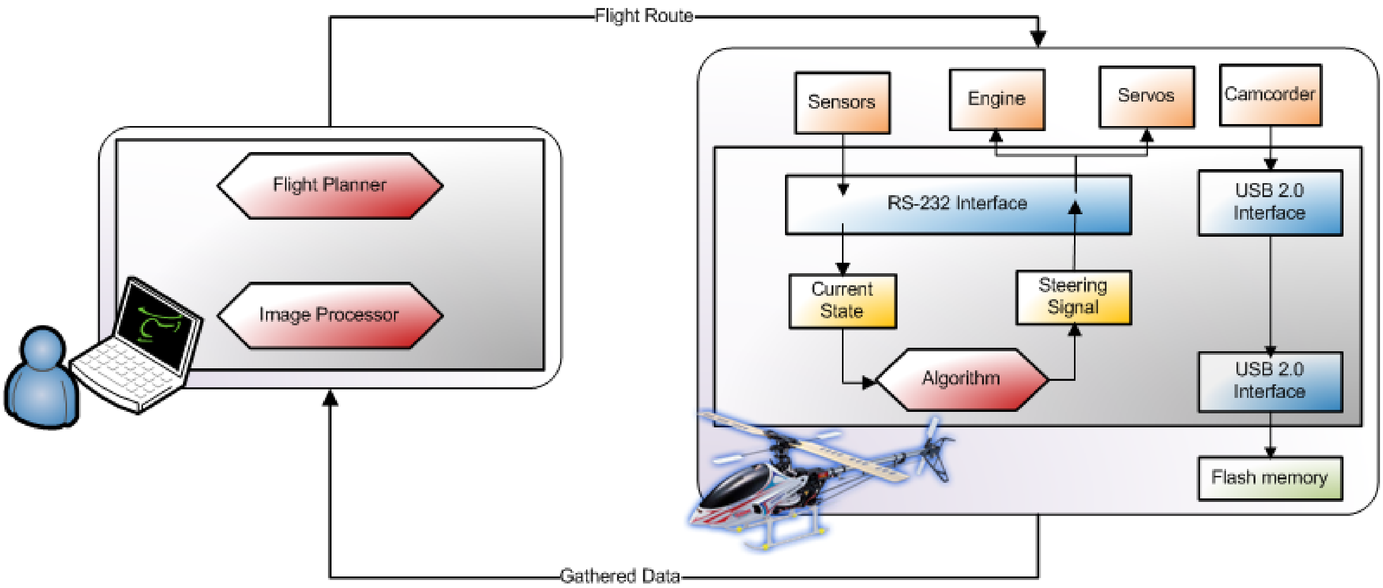


Figure 5. Data flow In the system

To effectively control the helicopter, a dedicated real time system is needed, providing high responsiveness and capable of dealing with significant amounts of data from the camcorder. Therefore our solution is based on eBox-4300 which acts like a small SCADA (Supervisory Control and Data Acquisition) system for our helicopter. Basically, it executes an infinite loop, consisting of 4 main steps:

- Every frame sent by the microcontroller is fetched.
- eBox calculates the current helicopter state, based upon the most recent data.
- The steering algorithm is used to compute steering values for engine and servos.
- The values obtained by steering algorithm are send to engine and servos, via RS232

Steering Algorithm

The eBox steering algorithm is divided into three layers. In the lowest layer, operation is based on a standard approach to steering in a closed circuit. Data gathered from sensors is converted into usable physical values representing the current helicopter state, such as altitude, velocities, angles (yaw, roll, pitch). We calculate these values using theoretical equations adjusted with parameters inferred in the calibration phase. Computed values are compared with desired states. Results of this comparison are translated to proper signals by PID regulators and then sent to the mechanical steering devices. The parameters of the regulators can be remotely tuned by our testing software during experiments.

Desired values are given by the middle layer, which defines the current maneuver, like turning and stabilizing position. It analyzes the current state and can also react for emergencies and change the current action. It is possible to extend this layer with a set of patterns representing behavior in typical situations.

The highest layer contains the overall mission plan defined by the operator (waypoints) and controls the steps needed to complete the objectives.

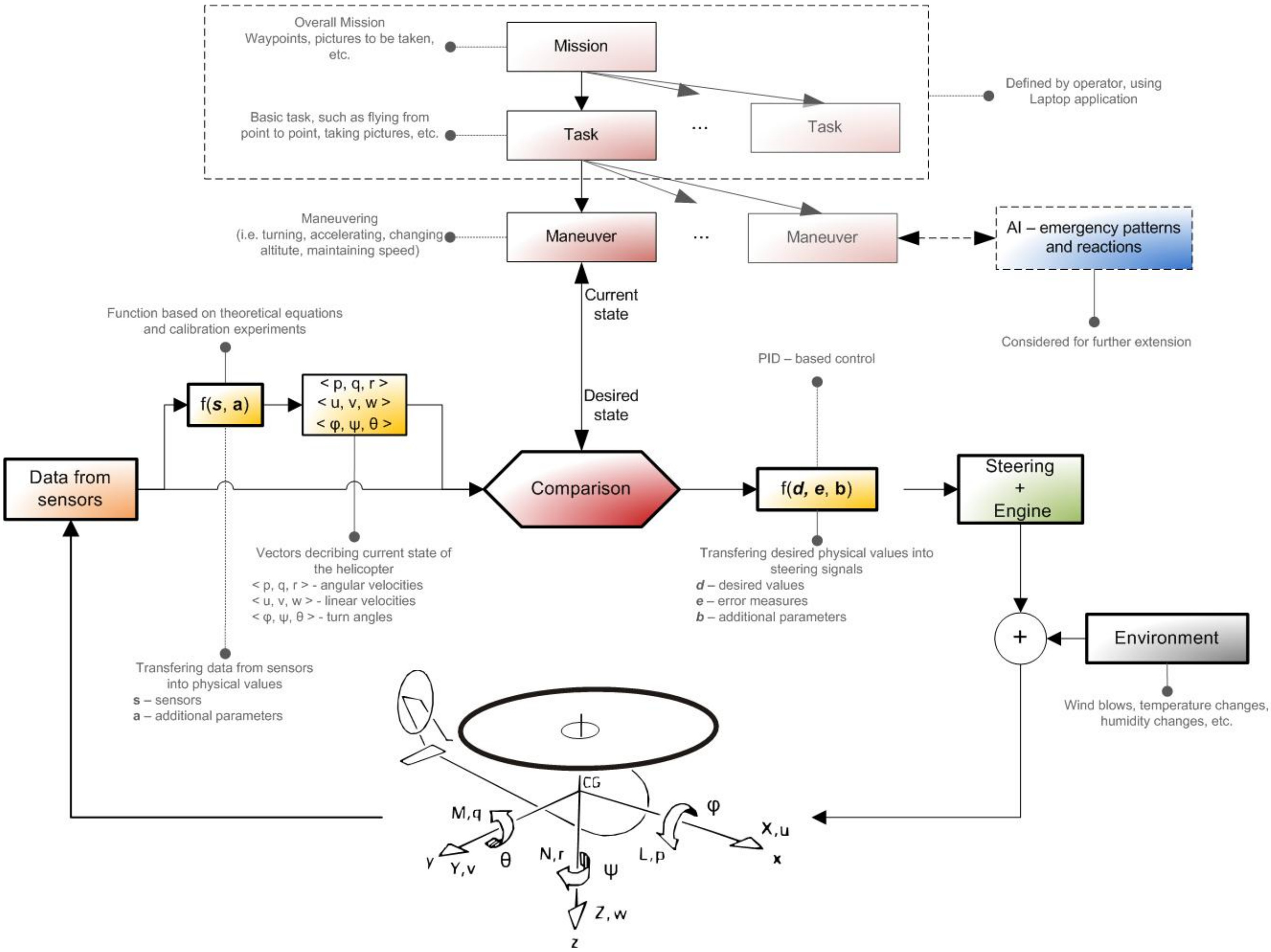


Figure 6. Steering algorithm diagram

In order to make the eBox application aware of the current helicopter state, we have to ensure every frame with sensor data is read with a minimum delay. 72 byte length frames arrive at eBox approximately every 5 milliseconds (at RS baud rate of 115 200 kbps). This gives us a hard real-time requirement which the flight control application has to meet - every iteration of the program's main loop should take no more than 5 milliseconds. The application is written entirely in unmanaged C++, since the real time processing environment disqualifies the use of unpredictable garbage collecting.

Beside controlling flight, the eBox software enables capturing of data from the USB camera. Pictures are stored in the flash memory, for future offline analysis. Through careful assignment of thread priorities we assured the process of dealing with the camera will not distract the steering application.

After landing, data gathered by eBox is transferred to the PC computer application, which provides the viewer with basic analysis tools for pictures shot during the flight.

For the PC platform we have also developed an application for defining the helicopter route. Using detailed maps from maps.live.com the user is able to pinpoint checkpoints for the helicopter airway, define flight constraints, i.e. minimal and maximal altitude. The route defined on the PC is subsequently sent to eBox, which uses it during the whole flight for course calculation. The PC application was written in managed C# code, with the use of WPF for an enhanced user interface experience.

Deployment Analysis

Development

We've carefully analyzed dependencies between components to create a flexible and paralleled work schedule. As a result, the development process was broken-down in two dimensions:

- Space – into main components of the system, described in the [Overall Architecture]
- Time – into small, short-term sprints

For each component we divided the development into several steps. Each sprint was a logically closed phase that completed the next step.

To start analyzing the system as early as possible, we created stubs for all the components. At first we used a simple simulator sending hard-coded data instead of real samples to a process on eBox that forwarded that data to a PC and a PC application that received and checked the data. These stubs were gradually filled or replaced by more featured ones. At each step, components were thoroughly tested to assure their robustness. For testing purposes we developed a few helper tools, described in chapter 'Tools developed'.

Most of the work on each component was being done independently. The protocols were designed to be versioned and backward compatible, so asynchronous changes wouldn't spoil all the communication. As a result, we could start developing software algorithms even before all the electronics were assembled.

Tradeoffs

During the design phase, and later in development, we had to consider a number of tradeoffs concerning technical and functional aspects of the project. The most important criterion was to comply with hard real-time requirements.

The first important choice was the programming language. Managed languages offer easiness of programming, but use garbage collectors, which disqualify them from hard real-time applications. Therefore, we chose not to use .Net Framework, but plain C++.

At first, we planned a Compact Flash interface with our own drivers for communication with the electronics. Eventually, we decided to use RS-232 standard, as it speeds up the development process – it required less effort on eBox as well as on hardware microcontrollers.

Because we couldn't afford a thermal vision camera, we decided to use only a simple USB webcam in our prototype. It essentially provides the same type of data and in future can be replaced or extended with a thermal camera. Because the camera image isn't crucial, it doesn't have to be processed in real-time, so USB interface is suitable here.

Tools developed

During the development, we have designed a set of tools to facilitate the process of building and testing the system. We wrote a simple program for the microprocessor, which could emulate the helicopter's sensors even before any electronics were built. This allowed for early tests of the software part of the system and independent development of the hardware part.

In an embedded system concerning a specific process, it is crucial to be aware of every parameter of this process. For this purpose, we created a PC application that collects records and visualizes sensor data from Ecopteron. Communication runs by wireless network, therefore we can have an on-line view of the situation during flight.

Thanks to the high platform independence of C++ code, we designed the core steering algorithm classes to run on a PC as well. It enabled testing the algorithm offline, with recorded data and comparing the output – steering signals – with the ones generated by a human pilot.

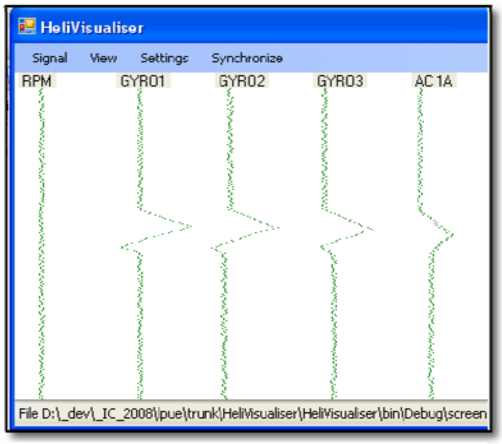


Figure 7. Visualisation application

Constraints and optimization

The constraints of our system were very strict. The helicopter has a small amount of weight it could carry - about 1kg. To minimize it, we had to remove the case from eBox, before attaching it to the vehicle. The less weight there is, the less power that is needed by the motor. With a 2.2Ah battery, we could not afford to waste any mWatt. The eBox application had to comply with real-time requirements, thus it was optimized to minimize response time. The CPU speed set the upper limit of operations we could complete in one loop.

As the helicopter is just a model, it cannot be used in extreme weather conditions like hard wind, rain, or snow.

To be accepted as a usable system, the Ecopteron should complete a set of tasks:

- A Use-Case task of a 'patrol' flight
- Safely landing if battery power is too low

- Avoid landscape obstacles on the path of flight

Performance Analysis

The quality of our project depends on careful design and precise realization of hardware components and eBox software. Therefore, assuring the highest performance of these parts is our main aim from the very beginning of the design process.

Five microcontrollers installed in the helicopter provide highly reliable communication with multiple sensors. Although we would be able to develop the same functionality using only one more powerful microcontroller, introducing such a redundancy enables **Ecopteron** to remain in working order even when up to two microcontrollers fail (even a limited group of sensors is sufficient to land safely).

Hardware components provide data, which has to be analyzed online by eBox software in order to produce a reasonable steering signal. Execution of the eBox application is subject to hard real-time requirements as the helicopter must react with minimal delay. Therefore, software was tested in terms of execution time. Another very important issue is power consumption. The less power that is required, the greater the helicopter's range. Increasing the range will notably enhance **Ecopteron** usability as the system will be able to monitor a larger area without charging. To further minimize power consumption we are going to remove some unused chips from the eBox motherboard, e.g. the audio chipset.

Even the most sophisticated system is useless when nobody knows how to use it. Thus creating an intuitive, user-friendly interface was also our concern. This aim is fulfilled by the laptop application, enabling the setting up of the route for the helicopter, monitoring its state and fetching data collected during the flight.

Ecopteron performance analysis is summarized in the following table.

Requirement	Ecopteron answer
Reliability	Redundant microcontrollers and sensors Comprehensive software tests
Power consumption	15 minutes of constant work on battery (average workload): helicopter at medium gear, eBox executing floating point numbers addition and multiplication in infinite loop
Range	15km (at average speed 60km/h)
Hard real-time requirements	Estimated time of single iteration of steering algorithm loop : 3ms
User friendly interface	WPF laptop application

Table 4. Performance analysis

Testing procedures & safety

One of the most important issues in designing unmanned vehicles is minimizing the risk of a crash which could not only destroy valuable hardware but above all jeopardize safety of people in the area. To ensure maximum safety we introduced complex testing procedures, covering both software and hardware components:

- Software unit tests. The most important methods were tested separately against random and manually chosen data.
- Software tests using sensor simulator – a simple microcontroller application writing to RS – this was used to verify correctness of the eBox data acquisition module.
- Real-time requirements testing. Code execution time measuring was added to the eBox application, enabling optimization of essential flight control methods, which consumed too much time.
- Hardware was developed in an incremental way: after adding new sensors its installation and operation were verified in two independent ways: with the use of the oscilloscope and by PC software developed by us for data visualization.
- For the final integration test we prepared a stand which upholds the helicopter during air tests in order to prevent hardware and equipment damage.
- Power consumption tests. We have measured how long the helicopter and the eBox were able to operate on a fully charged battery. During the test we were executing simple programs infinitely adding and multiplying floating point numbers on the eBox. The helicopter engine was on, at medium gear.

To enhance the reliability of our device we have installed a redundant accelerometer and gyroscopes, enabling efficient flight control even when some hardware components fail, at the cost of slightly bigger power consumption. The helicopter is equipped with supersonic sensors capable of detecting obstacles and enabling course adjusting. In case of sudden wind blows, strong enough to prevent effective steering, the helicopter will try to land. The Operator, thanks to autonomous remote control circuit, is also capable to take over the control in emergency situations. Future plans include implementing an autorotation mechanism, allowing landing even when an engine problem occurs. After an emergency landing, the helicopter can be found thanks to the attached emergency radio transmitter.

Additional safety is ensured by the laptop application, which will force the operator to set a route avoiding inhabited places. Basing on known forest area it will also properly adjust minimal flight altitude. Before takeoff eBox compares route length with the battery power level and will refuse to start if calculations indicate not enough battery life to return.

Embedded Analysis

Embedded Image and hard real time analysis

While designing the Windows CE image, our target was to use only necessary components, thus minimizing the number of system modules loaded and processes running. We needed all available processor time for our process. The most important components of our image are:

- USB Camera Driver
- USB NDIS driver – for USB wireless module
- ATADISK driver – for storing recorded data on a CF Card
- Serial Port Support

A few problems have arisen during construction of the embedded system. The hardware platform – eBox-4300 seemed to randomly hang while inserting a USB device. The solution was to simply use a USB cable extender. In the software part, there were problems with USB camera drivers. It turned out that our camera was not supported by the drivers and we had to find a supported model.

Hard real-time analysis

Apart from the time bounds on ISRs and the threads scheduling guaranteed by the operating system, we needed to ensure that every event registered by sensors would be served on time. Using an oscilloscope, we've measured the time taken to observe a change in the sensor's value on eBox and the time of the program reaction. The results are shown in Table 5.

	Action	Time[ms]
Communication	Sending one frame [72 bytes]	6,25
	Parsing the frame	0,58
	Sending reply frame [20 bytes]	1,7
	Overall Communication	**8,53**
	Steering algorithm loop	~3
	Total	**11,53**

Table 5. Measured communication timings

As a test if our system is fail-safe, we designed a simulation of hardware malfunctions. Sending a lot of malformed frames can simulate communication problems and sending random data instead of some sensor's bearing can simulate sensor malfunction. Results of these tests will confirm the robustness of our system.

Embedded Software Design

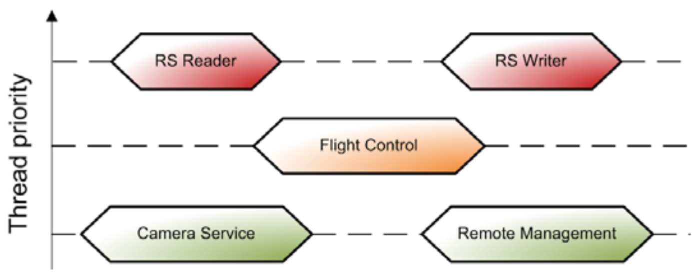


Figure 8. Threads organization

Designing a flight control application, which has to meet hard real-time requirements, enforced us to carefully consider the application architecture. As the eBox application, in order to meet desired functionality, has to be multithreaded, we have spent a lot of time focusing on proper thread organization. Taking advantage of Windows CE scheduling algorithm, we have decoupled eBox software logic into 5 cooperating threads, as shown in figure 8.

Two threads with the highest priority are responsible for reading and writing data from RS. It is essential to get the most recent information from sensors and timely send steering commands to the servos, so we have to be sure no other thread will take precedence before these two. Highest priority threads will be spending a vast majority of time executing input output operations, thus giving enough CPU time for the flight control calculation thread. Additionally we have two lower priority threads – the camera service thread and the management thread.

The management thread enables setting the steering algorithm parameters and monitoring the current **Ecopteron** state via a TCP connection. This feature lets us reconfigure the application without recompilation and deployment, thus saving much time during tests. It can be also used to change flight plan after takeoff, without requiring **Ecopteron** to return to the operator.

Embedded Component

The embedded device – eBox-4300 was chosen for controlling the helicopter. Because of the dimensions of the vehicle and the limited power supply, it would be impossible to use a PC instead. An alternative was to use a microcontroller. While it would be feasible, eBox has a lot of advantages:

- **Easier development** – no hardware dependent code needed, a lot of advanced tools for debugging and profiling – almost no learning curve.
- **Robust, real-time operating system** provided 'out of the box'.
- **Extensibility** – effortless adding of USB devices, wireless module and memory cards.

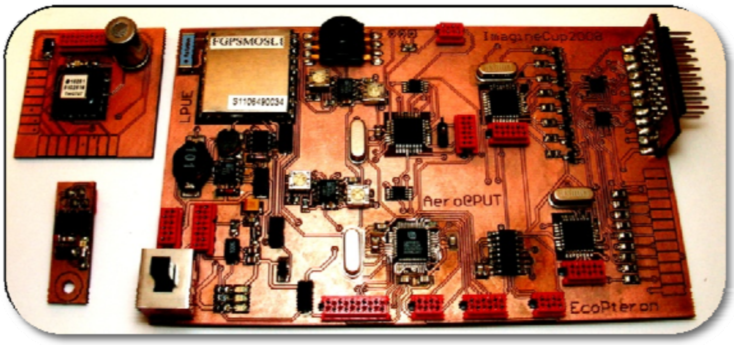


Figure 9. Ecopteron's electronics mainboard

Its most important disadvantage is higher power consumption. Because our system is intended for rather short flights, we can accept that.

Project Status

The design of the components is based on the spiral model. Each increment was a functionally more complete and efficient version compared to the previous ones. This approach allowed for early prototyping, providing us with an indication of the main characteristics and limitations of the system functionality.

Thanks to Microsoft's Solutions Framework, we adjusted methodology to specific characteristics of our project. **Ecopteron** project has been divided into five phases: envisioning, planning, building, stabilizing and testing phase. The first two of them were conducted by sharing the vision of every team member. The following three are based on empowering each team member to take responsibility for management, design and the development of certain system modules, according to their skills and experience.

We established a highly collaborative and self-managing team, consisting of four motivated, willing to learn peers knowing their roles well in the project and enjoying it.

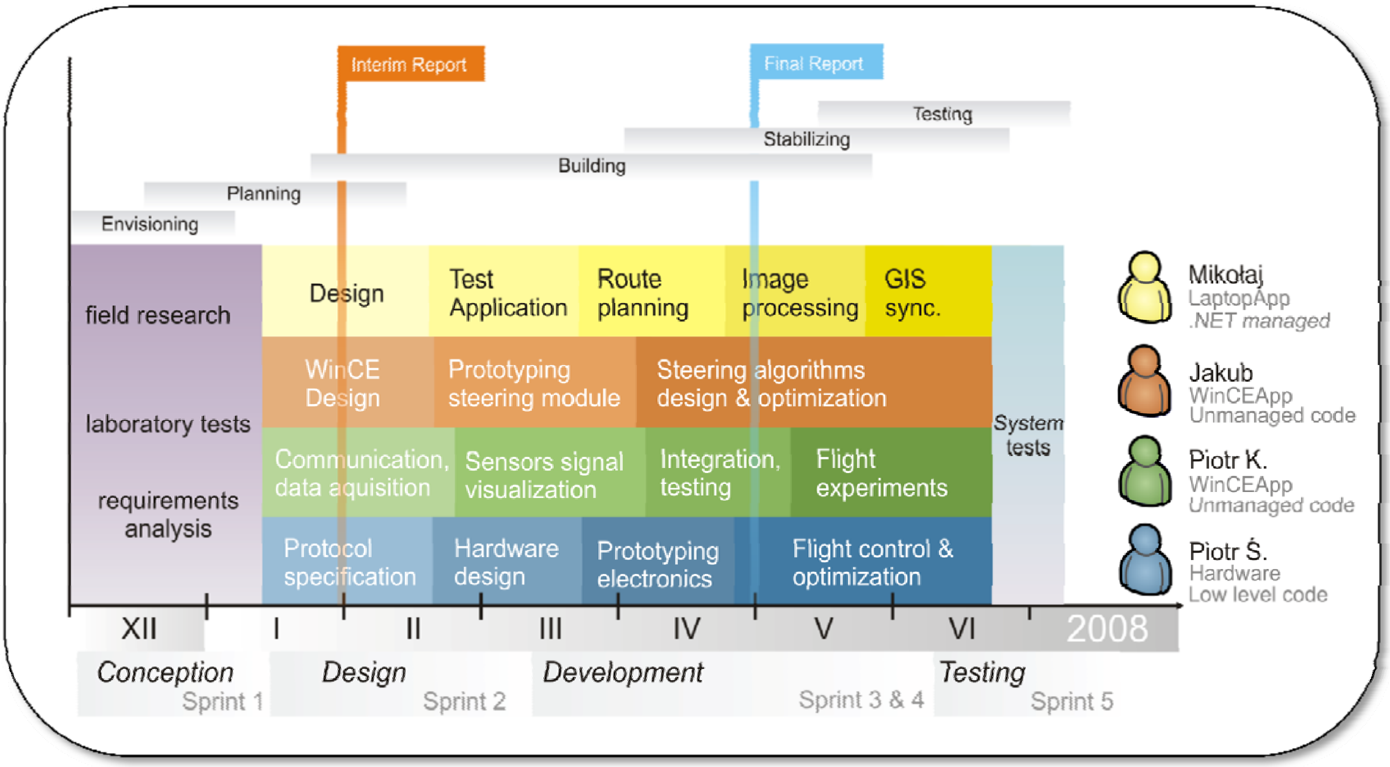
Taking advantage of modern software development tools, we could build our application in a relatively short period of time. Agile organization of our teamwork appeared to be more suitable for the project than more formalized methods.

According to the MSF suggestion, in our teamwork much attention is paid to the open communication between team members. We have introduced regular team meetings every week, organized voice conferences, shared documents via the project server and controlled work progress using Trac's ticket system. It was crucial for a smooth cooperation, while one of us, Mikolaj, is currently studying in Germany and participates remotely in the project. This approach enables each team member to know thoroughly the project and fully commit their knowledge and ideas.




- environment analysis, requirements analysis, software development (**Laptop application**) - Mikołaj

- system architecture, software development (**Helicopter AI, communication**) - Jakub
- quality control, testing, software development (**WinCE application, tools**) – Piotrek K.
- hardware design & development – Piotrek Ś.



Conclusions

The development of the **Ecopteron** project has brought us a great deal of new experiences. We have worked in a geographically distributed team, utilizing communication via the Internet and web project management tools to a great extent. Meetings with the environmentalists from the Polish Academy of Sciences - prof. Andrzej Kędziora and prof. Zbigniew Kundzewicz – not only have helped us to envision our project but have also taught us of the current environmental state and its threats. We have also studied details of helicopter physics, to develop efficient algorithms controlling the helicopter in terms of a hard real-time application. Still, this part requires more work, as the steering algorithm is not fully-fledged yet.

Knowledge acquired through meetings with specialists as well as by our own study, enabled us to introduce **Ecopteron** – the innovative device allowing for the flexible and inexpensive monitoring of numerous environmental processes, i.e. elements of energy and water balance over a range of landscapes. Better understanding of the role they play on the local scale will certainly lead to more appropriate decisions in landscape management, which directly influence the sustainability of the environment. The use of small, lightweight, unmanned, self-navigating helicopter equipped with sensors which allow for a remote sensing of the temperature and capturing the aerial photographs of ecotones, crop fields or water reservoirs regularly, provides the local landscape architects and community of farmers with valuable information about the current and the long-term environment condition in the region. Availability of such information will let those groups be better prepared for current season anomalies as e.g. pests or insufficient water resources as well as more successfully adjust regional policy to unavoidable climate change. In the future we consider further research leading to the introduction of enhanced functionality, including monitoring of spatial concentration of greenhouse gases in a region or early detection of environment disasters, such as forest fires.

Ecopteron's flexibility makes it attractive from the economical point of view. The ease of development of new features, coming directly off an application of a modular real-time operating system and careful design of hardware components, enables us to adjust our product to precisely fit customers' needs. A reliable flying helicopter, controlled by the embedded system, will certainly apply in almost any domain you can **imagine**.

The adoption of our solution by municipalities will be a small step towards a **more sustainable environment**, which is one of the most important goals of modern societies.