Master's thesis

Embedded Computer Including Software for the Intelligent Bird Nesting Box

Bc. Petr Kubizňák

2014

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Acknowledgement

I would like to thank all people who helped me in any way with this work. Especially my girlfriend for all her love and everyday care. My family for overall support. Members of this project for great cooperation and supervision. Elnico s.r.o. for providing development tools and exhaustive technical support. All business partners who helped with components selection or otherwise participated. And last but not least all developers of free and open source software without which this work would never come true.

Declaration

Abstrakt

Tato diplomová práce popisuje návrh a implementaci autonomního kamerového systému, vestavěného do ptačí budky. Tento systém je požadován týmem ornitologů pro výzkum sýce rousného v jeho přirozeném životním prostředí. Nejprve je navržena sestava hardwarové výbavy, která je následně vyvinuta a vyrobena firmou Elnico s.r.o. dle potřeb systému. Poté jsou vybrány platformy Linux OS® a Freescale MQX™ RTOS pro paralelní běh na dvoujádrovém mikroprocesoru řídícím hlavní desku. Pro tyto operační systémy jsou vyvinuty aplikace pro pořizování videa a řízení systému, prostředí je nastaveno pro umožnění přístupu k datům a konfigurování zařízení. Při každém vniknutí sovy do vletového otvoru budky vzniklý systém zaznamenává video záznamy ve vysokém rozlišení společně s identifikačními údaji sovy a data o současném stavu prostředí. V závěru jsou prezentovány výsledky prvních experimentů po umístění zařízení do cílového prostředí na začátku hnízdní sezóny roku 2014.

Klíčová slova

Kamera; monitorování; sovy; vestavný systém; sběr dat

Abstract

This diploma thesis describes design and implementation of an autonomous video surveillance system embedded in a bird nest-box, needed for research of boreal owl in its natural environment. First, a custom hardware equipment is proposed and designed. It is then developed and manufactured by Elnico s.r.o. Linux OS® and Freescale MQX™ RTOS operating systems are selected as software platforms running on a dual-core microprocessor in parallel. Video recording and system control applications are developed and the environment set up to allow data access and system configuration. The resulted system produces high-definition video records triggered by a bird passing through the fly-in hole, the bird identification and environment conditions data. Results of the first experiments after deployment in the forest in nesting season of spring 2014 are presented.

Keywords

Camera; Monitoring; Owls; Embedded; Data acquisition

České vysoké učení technické v Praze
Fakulta elektrotechnická

Katedra kybernetiky

ZADÁNÍ DIPLOMOVÉ PRÁCE

Student:	Bc. Petr K u b i z ň á k
Studijní program:	Otevřená informatika (magisterský)
Obor:	Počítačové vidění a digitální obraz
Název tématu:	Vestavný počítač a jeho programové vybavení pro inteligentní ptačí budku

Pokyny pro vypracování:

1. Navažte na výzkumný projekt A4M33SVP, který jste řešil v minulém semestru, v němž jste se s tématem seznámil.
2. Navrhněte a vytvořte systém pro sběr dat s procesorem Freescale Vybrid VF6, který bude základem inteligentní ptačí budky, a připojte k němu potřebné periferie (dvě kamery, dva osvětlovače, světelná závora, čtečka RFID, WiFi modul a případně dálkové ovládání).
3. Navrhněte a vytvořte systémový software pro budku nad operačními systémy MQX a Linux.
4. Navrhněte a vytvořte aplikační software inteligentní ptačí budky.
5. Spolupracujte s ornitology z České zemědělské univerzity v Praze při vestavění počítače do budky a respektujte jejich uživatelské požadavky při vývoji počítače budky.
6. Výsledky zdokumentujte z návrhového i uživatelského pohledu.

Seznam odborné literatury: Dodá vedoucí práce.

Vedoucí diplomové práce: Ing. Pavel Krsek, Ph.D.

Platnost zadání: do konce zimního semestru 2014/2015

L.S.

doc. Dr. Ing. Jan Kybic	prof. Ing. Pavel Ripka, CSc.
vedoucí katedry	**děkan**

V Praze dne 20. 8. 2013

Czech Technical University in Prague
Faculty of Electrical Engineering

Department of Cybernetics

DIPLOMA THESIS ASSIGNMENT

Student:	Bc. Petr K u b i z ň á k
Study programme:	Open Informatics
Specialisation:	Computer Vision and Image Processing
Title of Diploma Thesis:	Embedded Computer Including Software for the Intelligent Bird Nesting Box

Guidelines:

1. Follow your own research project A4M33SVP, which you solved in the past semester and which introduced you into the topic.
2. Design and implement data collection system with the processor Freescale Vybrid VF6, which will be the core of the intelligent bird nesting box, connect necessary peripherals to it (two cameras, two illuminants, light curtain, RFID reader, WiFi module and potentially a remote control).
3. Design and implement system sw for the intelligent bird nesting box based on operating systems MQX and Linux.
4. Design and implement the application sw of the intelligent bird nesting box.
5. Collaborate with ornitlogists from the Czech University of Life Science Prague in embedding the computer into the nesting box and take into account their user requirements while developing the nesting box computer.
6. Document your results both from a designer and user point of view.

Bibliography/Sources: Will be provided by the supervisor.

Diploma Thesis Supervisor: Ing. Pavel Krsek, Ph.D.

Valid until: the end of the winter semester of academic year 2014/2015

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Head of Department

prof. Ing. Pavel Ripka, CSc.
Dean

Prague, August 20, 2013

Contents

Abbreviations

List of standard and few own acronyms and abbreviations.

A5	ARM® Cortex™-A5
ACK	acknowledge
ADC	A/D converter
API	Application Programming Interface
ASCII	American Standard Code for Information Interchange
AVI	Audio Video Interleave
bps	bits per second
BSP	Board Support Package
CCD	Charge-coupled Device
CMOS	Complementary Metal–Oxide–Semiconductor
DC	Direct Current
DCT	discrete cosine transform
DDR	Double Data Rate
ESL	Elnico Support Library
FFS	Flash File System
fps	frames per second
FTM	FlexTimer
FTP	File Transfer Protocol
GCC	GNU Compiler Collection
GDB	GNU Debugger
GNU	GNU's Not Unix
GPIO	General Purpose Input/Output
GPL	General Public License
HD	High Definition
HEX	hexadecimal
HTTP	Hypertext Transfer Protocol
HW	hardware
I^2C	Inter-Integrated Circuit; also IIC or I2C
ID	identifier
IDE	integrated development environment
IP	Ingress Protection
	Internet Protocol
IPC	inter-process communication
IR	Infrared
IRBAR	infrared light barrier
JPEG	Joint Photographic Experts Group
LED	Light Emitting Diode
LGPL	Lesser General Public License
M4	ARM® Cortex™-M4
MCC	Multi-Core Communication library
MCFS	Multi-Core File System
MCU	Microcontroller Unit; microcontroller
MFS	MS-DOS File System
MPU	Mcroprocessor Unit; microprocessor
NACK	non-acknowledge
OS	operating system

PC	Personal Computer
PCB	printed circuit board
PGM	Portable GrayMap
PIT	Passive Integrated Transponder
PSP	Processor Support Package
PWM	Pulse Width Modulation
px	pixel
RAM	Random Access Memory
RFID	Radio Frequency Identification
RFS	Root File System
ROM	Read-Only Memory
RTC	Real-time Clock
RTCS	Real-Time Communication Stack
RTOS	real-time operating system
SD	Secure Digital
SW	software
SIP	System-in-Package
SOM	System-on-Module
SPI	Serial Peripheral Interface
TCP	Transmission Control Protocol
TCP/IP	Transmission Control Protocol/Internet Protocol
UART	Universal Asynchronous Receiver/Transmitter
UI	user interface
USB	Universal Serial Bus
V4L	Video4Linux
WDOG	watchdog

Names and Trademarks

List of often used company names and their products and trademarks.

ARM	ARM®
Cortex	Cortex™
Elnico	Elnico s.r.o.
Enika	Enika.cz s.r.o.
Factory	LinuxLink Factory
Freescale	Freescale Semiconductor, Inc
IDS	IDS Imaging Development System GmbH
Linux	Linux OS®
MQX	Freescale MQX™
SQM4	SQM4®
Timesys	Timesys Corporation
Windows	Microsoft™ Windows® OS

1. Motivation

The assignment of this diploma thesis is motivated by the research of Ing. Markéta Zárybnická, Ph.D. from the Czech University of Life Sciences Prague. She is interested in geographical variation in breeding and foraging strategy of the Tengmalm's owl (*Aegolius funereus*). The Department of Cybernetics of the Czech Technical University in Prague, Faculty of Electrical Engineering cooperates at the activity. I was asked to help the effort in my diploma project by developing and constructing an autonomous computer system.

My motivation to participate in this project was based on my interest in practical tasks. I also have the advantage that my father owns company Elnico s.r.o., which develops and produces embedded electronics. Hence I have access to hi-tech embedded technologies needed for this project.

My work contributes to a new type of a computerized nest-box enabling the data acquisition and monitoring of owls nesting in nest-boxes located in their natural environment. The nest-box is hung usually on a tall tree in the forest. It has an own battery allowing its autonomous operation.

The project requires a video surveillance system embedded in every nest-box to record a fly in of an owl (typically a male) bringing the prey, usually a small mammal (*Microtus* vole or *Apodemus* mouse) or a bird. The data needed for identification of individual owls and the type of food supply are recorded.

Such a system has been developed and is described in this thesis. Monitored owls are equipped by Radio Frequency Identification (RFID) chips. The owl identification has been based on RFID technology. To identify the type of the prey, the expert human recognition is required, as there is a high variety within hunted species. For this sake, a pair of Infrared (IR) High Definition (HD) cameras is used. The first camera records the entrance hole. The second camera records the nest-box ground. Both cameras are equipped with an IR flash. The system is further equipped with an IR optical barrier to detect owls flying in the nest-box and reduce memory and power requirements by starting the recording only at the time of an event of interest and stopping it afterwards. Two temperature sensors and one sensor of the ambient light are included to provide more information about nesting for research purposes. All captured data is stored permanently on a local filesystem and can be collected through a File Transfer Protocol (FTP) connection, using a wired local network. The whole system is powered by one 60 Ah 12 V traction battery which allows for approximately one-week long autonomous operation of the system.

2. Task Formulation

Requirements on the embedded system to be developed are given by the planned research project described in [1]. Authors of the project are researchers from a team from the Czech University of Live Sciences Prague, Faculty of Environmental Sciences, Department of Ecology, leaded by Ing. Markéta Zárybnická, Ph.D. They will be further referred to as the *ornithologists* in this document. The main focus of the project is posed on the camera surveillance system: "*The principal task is to record an owl adult while bringing the prey into the nest-box and determine the prey species. The male owl quickly approaches the nest-box opening and in most cases only throws the prey inside. The secondary task is to monitor a nesting area on the bottom of the nest box to gain additional information on prey determination, prey decapitation and owl behaviour (e.g., sibling competition).*" This means the system has to contain two cameras, the first recording the fly-in hole and the second recording the nest-box ground. Since the owls are active at night, a lighting has to be used to provide the cameras sufficiency of light. To prevent disturbance of the birds, source of light invisible to them shall be used.

To allow for identification of adult owls, each of them is fitted with a Passive Integrated Transponder (PIT) tag of type *EM4200*, readable by any compatible RFID reader. The tag should be scanned each time an owl approaches the fly-in hole, not depending on whether it enters or exits the nest-box or just brings a prey. On the other hand, the reader should not scan codes of birds present inside the box.

To improve the background of the scientific research, the system should be able to regularly measure temperature inside the nest and outside the nest-box, and exterior light conditions.

The system shall provide an easily accessible interface allowing to access the produced data and configure the main application settings. Preferable solution would be a wireless communication on standard TCP/IP protocols. The easily accessible RJ45 socket with the Ethernet connection might be used as a fall-back variant for case of the Wi-Fi failure or if the system needs to be mounted before the wireless functionality is implemented.

The output of the system will be:

1. Short video sequences (few seconds long, high frame-rates) of the nest-box fly-in hole, triggered by the prey delivery events.
2. Longer video sequences (few minutes long, low frame-rates) of the nest-box ground, triggered by the prey delivery events.
3. RFID codes of the adults delivering the prey, triggered by the prey delivery events.
4. The list of temperatures and ambient light measurements, triggered periodically.
5. All data will be marked with a time-stamp, giving time of its retrieval.

The minimal configurable options will be:

1. Video records lengths, adjustable separately for both cameras.
2. Video records frame-rates, adjustable separately for both cameras.
3. Camera exposures, adjustable separately for both cameras.

The system will be powered by a traction 12 V battery, which will be replaced regularly approximately once in a week. Ideal capacity is between 50 and 60 Ah, as the dimensions and weight of the battery grow significantly with the capacity, a bigger battery is hence inadvisable. The system should be designed with respect to minimum power consumption.

The system will run autonomously and fully automatically, no remote control mechanism is desired. Recorded data will be collected on weekly basis, together with the power supply replacement.

To achieve requested scientific value of the research, higher number of such intelligent nest-boxes is needed, the ideal count is twelve. That means that it must be possible to produce such a number of boxes for a reasonable price, so the components need to be selected with respect to the cost and availability.

3. State of the Art

Nest monitoring is a frequent task in life sciences, particularly in ornithology. It gives scientists valuable data about population growth, nest attentiveness, parental care, nest predation, birds' diet and birds' behaviour in general. Multiple different approaches can be taken, each limited by the observation purpose, observed species, financial and human resources and other constraints.

3.1. Direct Observation

A direct observation is technologically the simplest method used in nest monitoring. It is based on a periodic visual exploration of nests, either locally or from a distance (e.g. using binoculars). This method is useful mainly for checking the number of laid eggs, number of hatched chicks, whether the nest has not been abandoned or predated.

The first main limitation of this method is induced by the monitored species, which can either nest at inaccessible places (for example rocks) or be particularly sensitive to human presence.

The second constraint is a limited number of human resources in scientific research, as periodic checks of a scientifically sufficient number of nests may pose high requirements on time resources. Some researches or programmes try to solve this problem by popularization of the topic and gaining volunteers which collect the data for them. This is for example case of the *Michigan Bluebird Society*, trying to help and monitor the population of the *Eastern Bluebird*. Through a large community of so-called *landlords* (see Fig. 1), they manage to "*improve the nesting success of the Eastern Bluebird and other native cavity-nesting birds in the state of Michigan*" [2], USA.

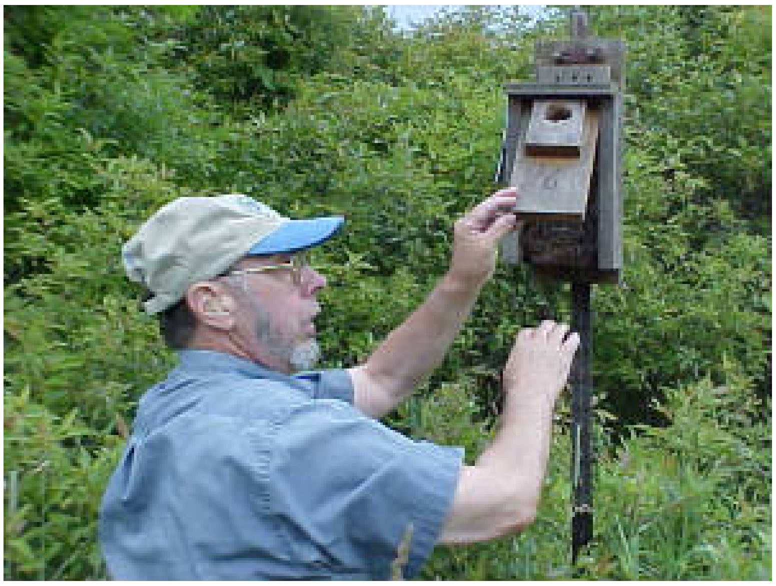


Figure 1. Landlord performing regular check of a nest-box. From [2].

3.2. Continuous Recording

A widely used technique is an autonomous video surveillance system equipped with a camera, a power supply and a data storage or stream. Such systems usually record one video sequence continuously (typically with a very low frame-rate – *time-lapse video*) or record shorter video sequences periodically with time delays.

These systems pose high requirements on the power supply and require either a large data storage and its periodical replacement, or a sufficient bandwidth of a wired/wireless connection allowing for streaming or downloading the data remotely. One of disadvantages is a high percentage of useless data when there is nothing happening inside the nest on one hand, and a high amount of potentially valuable events which are not recorded on the other hand.

This approach has been taken for a research of siblicide in bearded vultures (*Gypaetus barbatus*). To observe aggression between two sibling chicks and death of the younger one, the authors used quite complicated apparatus comprising of two parts: "*(1) a nest monitoring subsystem (camera, microphone, battery with a charge controller and a transmitter together with an antenna), which was supported by a solar panel, and (2) a recording subsystem (antenna receiver, video signal controller and a remote controlled PC through a GSM modem) that compressed the audio-video signal and provided real time monitoring.*" [3]. The nest monitoring subsystem featured a waterproof colour 640×480 camera with 1/3 inch CCD chip and a 3.6 mm lens with 78° wide field of view. It was scheduled to record one 15 minutes long video shot at the frame-rate of 25 frames per second (fps) every two hours. The control PC ran the Windows XP operating system. The system was powered by a 100 Ah battery supported by a 75 W solar panel without which the battery would discharge after a period of 4 days. The system structure is illustrated in Figure 2.

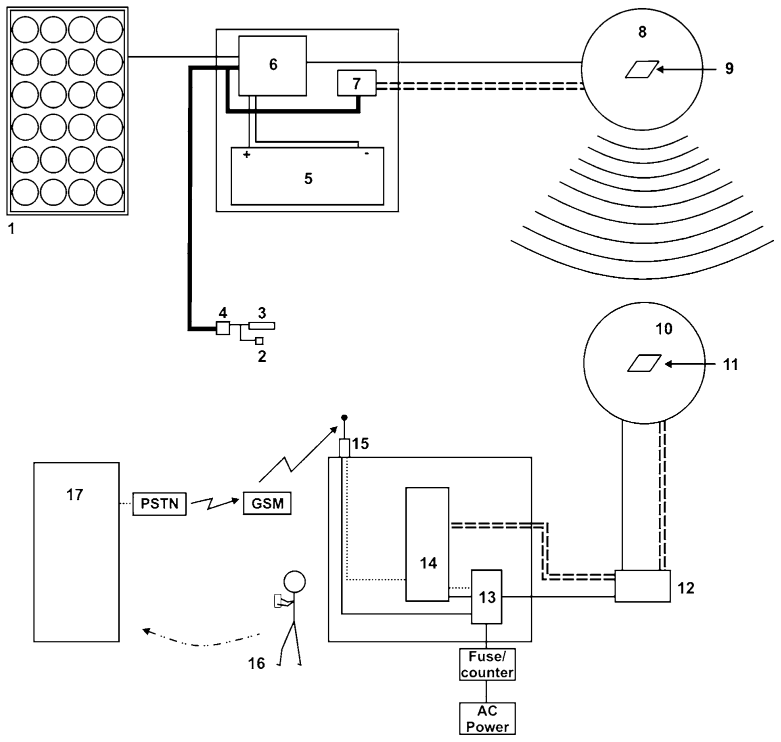


Figure 2. Structure of the video-surveillance system used to monitor a bearded vulture nest. 1–9 Nest subsystem, 10–16 local subsystem, 17 central subsystem. From [3].

A much simpler and probably cheaper equipment was used in a research of nest predation of Superb Fairy-wren (*Malurus cyaneus*) [4]. The recording system was based on an Apple MacMini computer, controlling and storing data from four waterproof video cameras *Eye Spy World* with 1/4 inch Sony CCD sensor. Each camera was powered by a small 12 V 12 Ah battery and connected to the recording system by a cable. The system was set to record continuously. To reduce the amount of data, the authors scanned 24 hours of one day only for variation in feeding activity during the day, as the highest predation risk is during feeding. According to that measure they selected 2-hour period in the morning and 2-hour period in the evening to be examined thoroughly in all records, the rest was ignored.

3.3. Event-based Recording

Recording systems equipped with event detectors help to automatically separate the interesting data from the rest, simplifying results evaluation and potentially saving power and storage resources.

One such system has been developed for monitoring nests of Tengmalm's owl and is described in [5]. The authors' functional requirements on the system abilities were:

1. *"Observation of movements of the nesting individuals between the nest and the environment.*
2. *Monitoring the times spent by an individual outwards the nest and in the nest.*
3. *Identification of the kind and type of prey.*
4. *Observing behaviour of nestlings and distribution of parental roles in the nesting period."* [5]

The requirements implied need of a night vision camera, that is a camera sensitive on IR light, and an IR flash to illuminate the content of the nest-box. The authors chose a DECAM camera module (SINIT, Czech Republic) equipped with 16 MB data memory, wireless data communication, two logical inputs and one output for lighting control. The camera was able to record 1-3 frames per second. The flash was constructed from 24 IR Light Emitting Diodes (LEDs) SFH485-2 with 880 nm wavelength as it was the closest match for expected ideal wavelength of 900 nm.

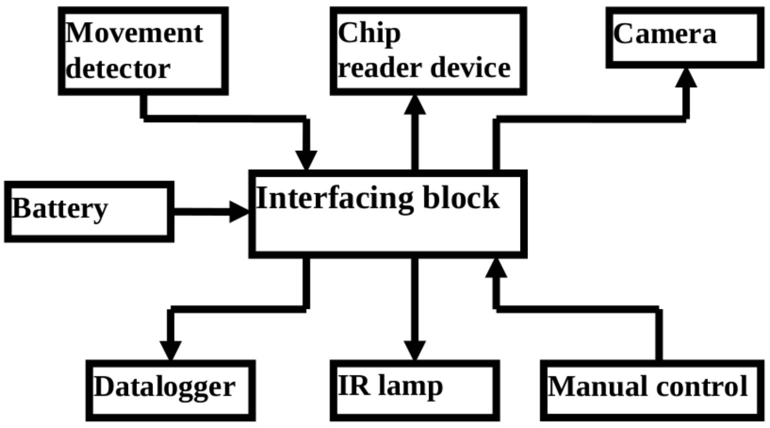


Figure 3. Conceptual design of device for monitoring nesting of the Tengmalm's owl. From [5].

As the used camera allowed for storing of a very limited number of pictures (1024, [6]), the system had to be equipped with a mechanism called *motion detector* so the camera could record only important scenes, filtering out all the rest when there is nothing happening in front of it. The motion detector was in fact an IR optical barrier constructed from through-beam sensors KS96 (Kotlin, Czech Republic, [7]) with the frequency modulation. The barrier was placed in the fly-in hole so the light beam must be crossed by the bird entering the box. The sensors could operate on 15-30 V DC.

The system was further equipped with a PIT tag reader device PS02 (Elvis, Czech Republic) with a circular antenna positioned around the fly-in hole, used to identify owls fitted with a PIT tag.

The entire system, illustrated in Figure 3, was powered by a 60 Ah 12 V traction battery which sufficed for 6-8 days operation.

4. Design

The event-based surveillance system from [5], described in Section 3.3, became a good model for the new system being developed. The requirements posed on both systems were practically the same, so the actual task was to redesign the system from [5] using the up-to-date technologies, allowing for more functionalities and better performance.

4.1. Hardware

The conceptual design of the system, depicted in Figure 4, is very similar to the design of the model system, shown in Figure 3. The main difference is in the number of cameras, which is two instead of one. Also, illuminants are controlled directly by the cameras. Important change, not visible from the figure, is that the image data is stored in a centralized data storage on the control board, so the amount of data is not limited by the size of cameras internal memories, as it was in case of [5].

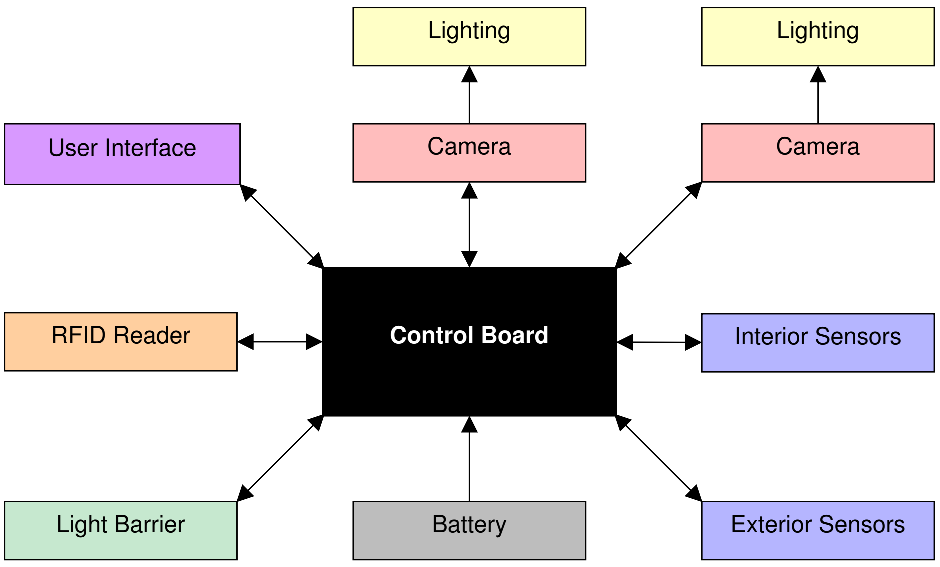


Figure 4. Conceptual design of the system hardware. The arrows symbolize the direction of communication/control.

Completely new items to the scheme are the interior and exterior sensor blocks, which were not present on the referential design.

The system uses the light barrier as an event detector, too (referred as *Movement detector* in Figure 3). Even though it might seem to be redundant since RFID reader could also be used for the same purpose, experiences with the referential solution have shown that the reader reliability is not completely satisfiable as the PIT tags sometimes fail to be scanned.

The following subsections describe briefly each block of the scheme in terms of what device has been selected and why, without discussing other alternatives as this has already been done in [8] in terms of the subject *A4M33SVP*.

4.1.1. Control Board

The central block of the system is a control board with the following requirements:

- Provides hardware interface to all needed peripherals,
- allows for running Linux OS® (Linux),
- is powered by a powerful microcontroller (MCU) / microprocessor (MPU),
- has a low power consumption,
- is well documented,
- is guaranteed to be available for several years,
- can be acquired for a reasonable price.

No commercially available solution fulfilling all listed requirements was found, so it was decided to let develop and manufacture a custom board. As a suitable platform, a new *Freescale Vybrid VF6* microprocessor was chosen, bringing all the features diagrammed in Figure 5.

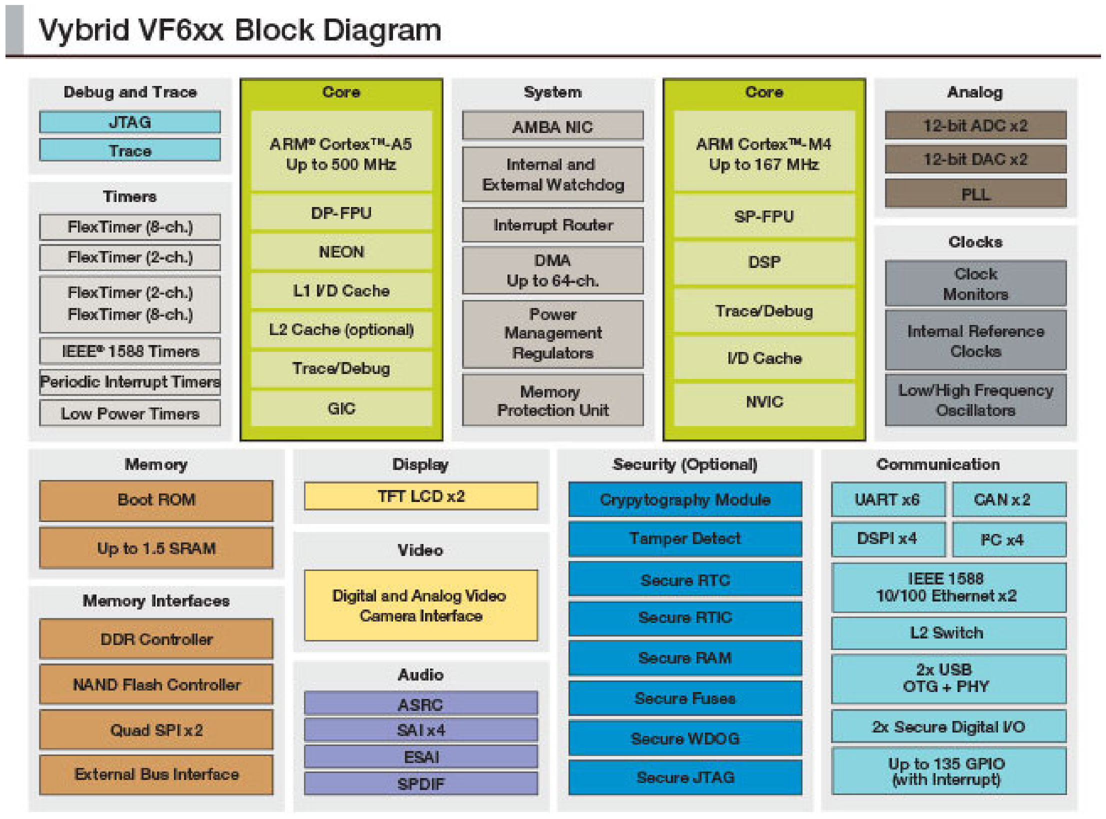


Figure 5. Freescale Vybrid VF6xx microprocessor block diagram. From [9].

The speciality of the microprocessor is its asymmetrical dual-core architecture, consisting of one 500 MHz ARM® Cortex™-A5 (A5) core, designated for running a high-level operating system (OS), and one 167 MHz ARM® Cortex™-M4 (M4) core primarily for low-level hardware operations. The ARM® (ARM) architecture is a guarantee for low power consumption and well-designed hardware. The microprocessor is new, available generally since January 2014, promising a long time support. And finally, there exists a processor module *SQM4-VF6-W* assembled with this MCU. It is manufactured by a Czech company Elnico s.r.o. (Elnico), commercially available from [10].

SQM4-VF6-W is a product from the SQM4® (SQM4) solderable processor modules series. Every device from this series is characterized as a System-on-Module (SOM), comprising a microcontroller/microprocessor with Double Data Rate (DDR) memory, NAND FLASH memory, Ethernet and Universal Serial Bus (USB) controllers on a squared module (16 cm^2), interfaced by so-called RIM connection with 160 pins. The RIM connection provides 4 variants of assembly, where one of them (*Down-pins*) is detachable, designed mainly for development purposes, while the others are solderable, providing a robust and reliable connection between the module and a base board.

The SQM4-VF6-W module, depicted in Figure 6, is comprised of a 256 MB DDR3 SDRAM memory, 256 MB FLASH memory, Dual Ethernet, USB and also an extra low-power WiFi modem, fulfilling the request on a wireless communication interface.

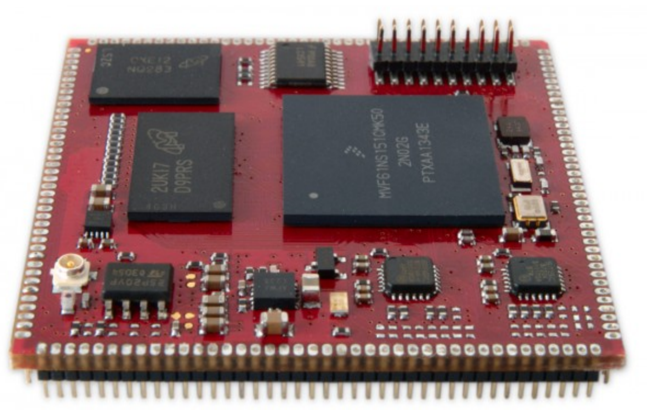


Figure 6. Photo of the SQM4-VF6-W module, the brain of the intelligent nest-box surveillance system. From [10].

Using the SQM4-VF6-W module, the development of the custom base board, named *BudkaControl*, became much simpler and hence cheaper task than it would be without it, as it reduced to a simple expansion board of the SOM. The peripheral scheme of the base board, illustrating the structure and assignments of the board peripherals to the peripheral devices, is depicted in Figure 7. The peripheral devices are described in the following subsections.

4.1.2. Cameras

The most attention in selection of peripheral devices was paid to the digital cameras, being the most important and expensive part of the system. It was decided to buy two monochrome industrial cameras *UI-1541LE* by IDS Imaging Development System GmbH (IDS), depicted in Figure 8. This type has the following features:

- Monochromatic CMOS sensor 1/2",
- resolution 1280×1024 px,
- maximum 25 fps,
- USB 2.0 interface,
- 1× external flash output,
- 1× external trigger input,
- 2× external GPIO,
- 1× external I^{2}C bus,
- free C/C++ API, Linux drivers and demos available.

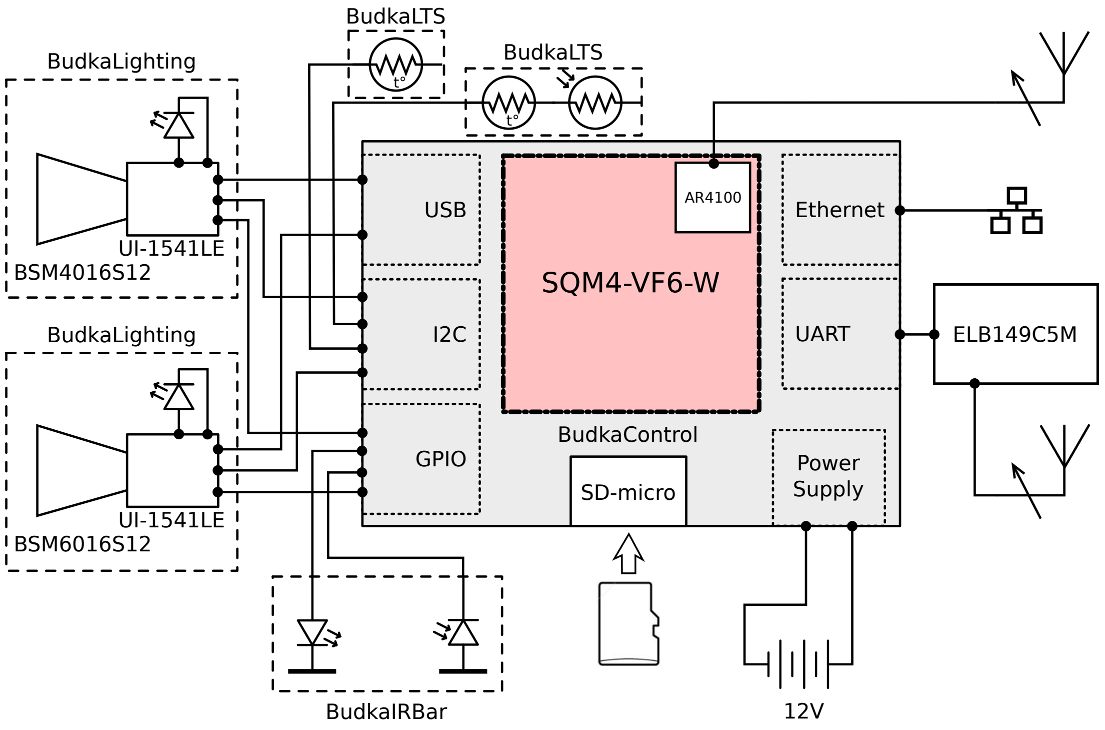


Figure 7. Peripheral scheme of the control board *BudkaControl*, depicting board peripherals assigned to peripheral devices.

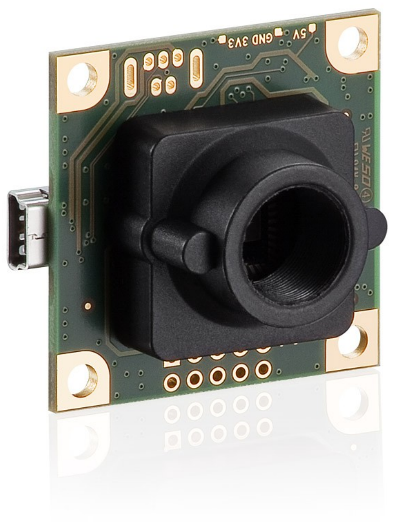


Figure 8. Photo of the UI-1541LE monochrome industrial camera. From [11].

Each camera should monitor different scene, implying different viewing angles, as illustrated in Figure 9. For this sake, different lenses were mounted on each camera. The *fly-in camera* was equipped by a lens *BSM4016S12* ($f = 4\ mm$, 96° horizontal field angle, S-Mount) to fulfil requirement of viewing the whole front side from the fly-in hole to the box ground, and the *ground camera* was equipped by a lens *BSM6016S12* ($f = 6\ mm$, 65° horizontal field angle, S-Mount) allowing for viewing the bottom half of the box. Both lenses are distributed by IDS, too.

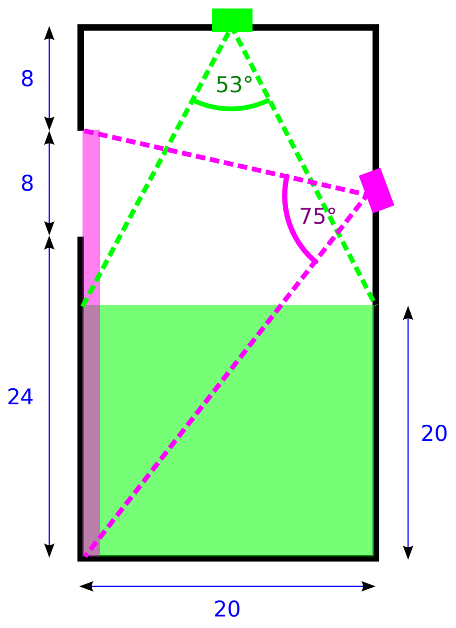


Figure 9. Approximate cameras viewing angles, derived from expected box dimensions (in centimetres). **Violet:** The *fly-in camera* and its required field of view. **Green:** The *ground camera* and its required field of view.

4.1.3. Infrared Lighting

The camera chip is not covered by any IR-cut filter, allowing for sensitivity on the IR light. Graph of the chip sensitivity with respect to the light wavelength is depicted in Figure 10. In the wavelength range of 700-900 nm, the chip sensitivity falls steeply with the growing wavelength, with only approximately 23% of full sensitivity at 900 nm wavelength. For this reason, the wavelength of the camera lighting should be rather close to 800 nm where the efficiency is much higher (about 40%).

Thanks to the external flash output of the UI-1541LE cameras, the lighting can be controlled right from the cameras. It was decided to develop a special board named *BudkaLighting*, implementing the infra-red lighting functionality. As the cameras have no covering, the board was designed to be directly connected to the camera and covered together in one box, protected on level at least IP54 (dust and partial water protection).

As the light source, *TSHG5510* IR LED by Vishay was picked. Main reasons for this type were its peak wavelength $\lambda_p = 830\ nm$ and a high angle of half intensity $\varphi = \pm 38°$, promising a uniform illumination of the whole scene. Graphs of the relative radiant power/intensity with respect to the wavelength and angular displacement are shown in Figure 11. More technical information can be found in [12].

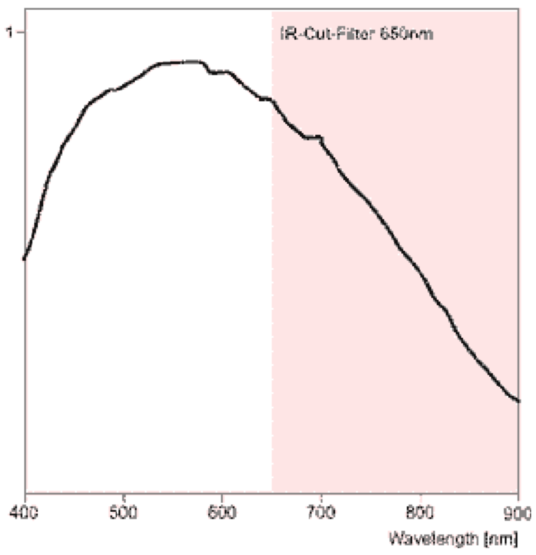
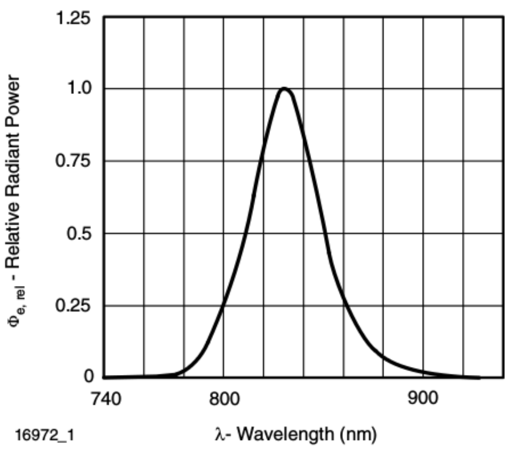


Figure 10. UI-1541LE-M-GL camera chip sensitivity on different light wavelengths. From [11].



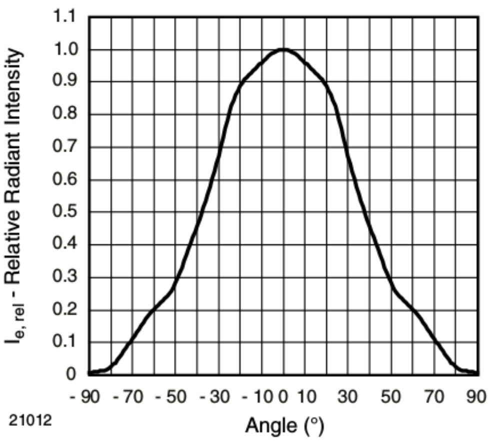


Figure 11. TSHG5510 HighSpeed Infrared Emitting Diode. **Left:** Relative Radiant Power vs. Wavelength. **Right:** Relative Radiant Intensity vs. Angular Displacement. From [12].

4.1.4. RFID Reader

Monitored owls are tagged with an RFID chip *EM4200*. It can be scanned by various commercially available RFID readers. The product *ELB149C5M* by Seeed Studio (see Figure 12) was found at [13] to be appropriate for this task. First it has relatively low power consumption (approx. 30 mA / 5 V), second it has a modular construction with a simple communication interface (UART, baud rate 9600 bits per second (bps), TTL output [14]) so it can be easily integrated into the system, and finally it is available for a very reasonable price.

The module is distributed with an external antenna which cannot be used though. A circular antenna around the fly-in hole, similar to the one used in the referential design (see Section 3.3), needed to be manufactured. Its dimensions are depicted in Figure 13.

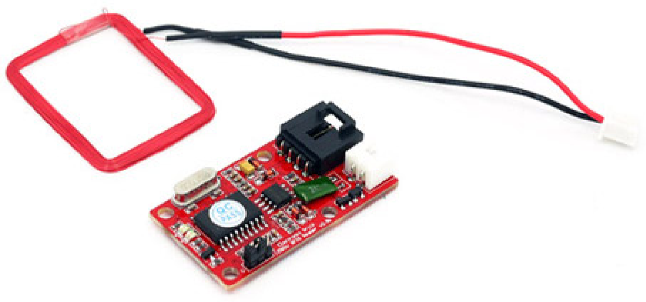


Figure 12. RFID chip reader ELB149C5M. From [13].

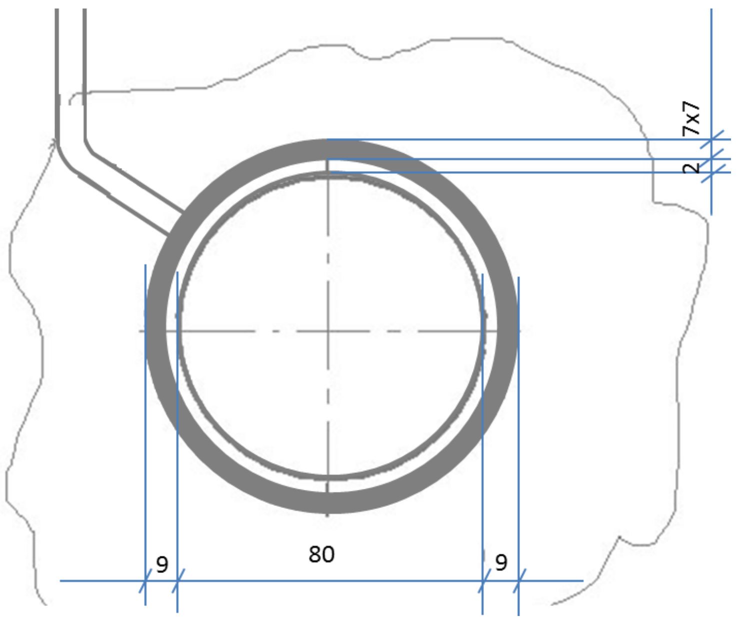


Figure 13. Custom RFID antenna dimensions requirements. Distances are in millimetres. (Edited drawing by the ornithologists.)

4.1.5. Light Barrier

The light barrier is an important part of the system functioning as the event trigger. It is a device consisting of one transmitter and one receiver. Transmitter is typically a LED, usually emitting an IR light. Receiver is located opposite to the transmitter and detects whether the space between both parts is clean, i.e. the light excites the receiver, or the beam is disrupted by a non-transparent object. The light is usually modulated by a periodic signal of a defined frequency, all other frequencies are filtered by the receiver, providing the high robustness against ambient light (sunlight, artificial light sources of different frequencies).

There are plenty of commercial products available on the market, being used for example for gate control or toilets flushing. These devices have usually a relatively high power consumption, big packaging and high cost. The majority of them (perhaps most of them) are also designed for too high voltage, often 230 V.

For these reasons, it was decided to develop and manufacture a custom light barrier on a board named *BudkaIRBar*. The receiver (*TSSP58038* by Vishay, technical specification in [15]) is designed for 38 kHz pulses of IR light with the highest sensitivity at 950 nm, and can be powered from 2.5 V to 5.5 V. The transmitter (*TSAL5100* by Vishay, technical specification in [16]) is a simple IR LED with peak wavelength $\lambda_p = 940\ nm$ and a narrow beam (angle of half intensity: $\varphi = \pm 10°$). The output signal of a required frequency needs to be generated by an external source. Pulse Width Modulation (PWM) peripheral of the processor will be used for that.

The board is designed to be placed in a groove milled in the front side of the nest-box, as illustrated in Figure 14. The board has a special shape so it goes around the fly-in hole and the light beam crosses the hole horizontally in the middle.

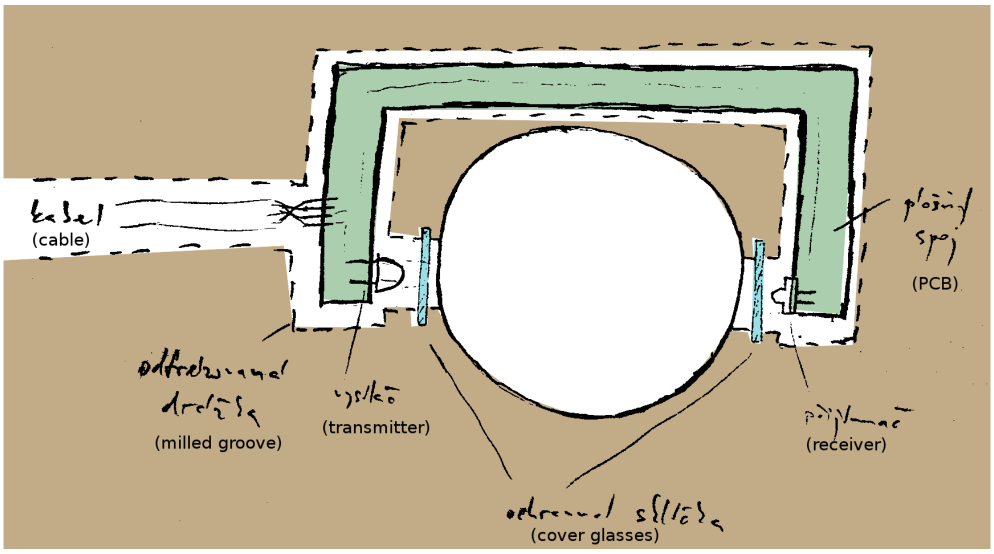


Figure 14. Illustration of the light barrier design and its placement in a groove milled in the front side of the box.

4.1.6. Temperature and Light Sensors

Interior and exterior sensors are designed as separate tiny boards named *BudkaLTS*. Both boards contain the temperature sensor (*MCP9804* by Microchip, technical specification in [17]) communicating on Inter-Integrated Circuit (I^2C) bus. In addition, the exterior sensors board features a 12-bit I^2C A/D converter, processing analog input from a photocell, implementing a light sensor. These parts are not placed on the interior sensors board.

The exterior sensors board is designed to be built in a nest-box side in such a way the photocell is in the box exterior. The interior sensor is not planned to be fixed on any place; on the contrary it should be on a loose cable so the ornithologists can place it for example amongst eggs and measure the temperature directly in the nest.

4.1.7. User Interface

According to the requirements, the user interface is designed to be realized by two hardware interfaces – *Ethernet* (a wired network) and *WiFi* (a wireless network). All needed controllers are implemented on the SQM4-VF6-W module. In case of Ethernet, only the *RJ45* connector needs to be placed on the base board. The WiFi is implemented by the Qualcomm-Atheros *AR4100P* chip.

The *AR4100P* is a small, single stream, 802.11 b/g/n WiFi System-in-Package (SIP) solution. It is primarily designed for applications hosted by low-resource microcontrollers that send infrequent data packets over the network. The system features extra-low power consumption, balanced by a lower throughput [18].

The chip is placed on the bottom side of the SQM4-VF6-W module, as shown in Figure 15. The module also features a tiny U.FL male connector on the top side, as visible in Figure 6. That can be used to connect the external WiFi antenna.

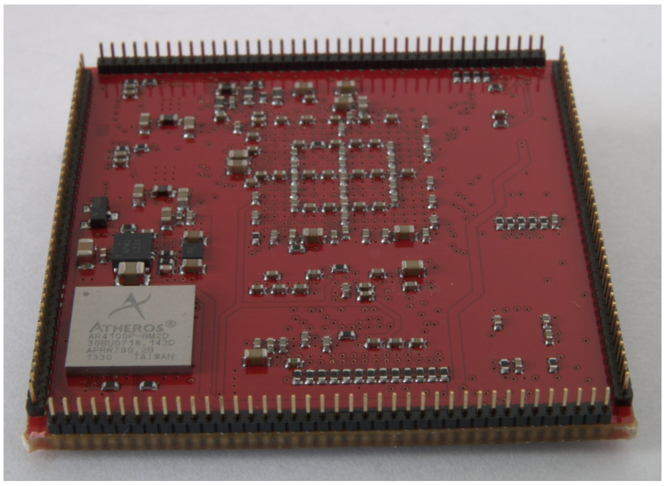


Figure 15. Bottom side of the SQM4-VF6-W SOM, with the AR4100P WiFi SIP by Qualcomm-Atheros.

4.2. Software

The main goal of this thesis is to develop an application serving all the hardware described in Section 4.1 and implementing all the functionalities described in Chapter 2. The application has been named *Birdhouse*.

The most general application flowchart is depicted in Figure 16. After powering on the device, the system boots, and depending on the daytime, it enters either a *Sleep mode* with most of the peripheral hardware powered off (light barrier, RFID reader, cameras), or a *Ready mode*, with all its hardware powered on.

In the *Sleep mode*, only the temperature and light sensors are periodically read out with a predefined time period. In the *Ready mode*, besides the periodical sensors read-outs, recording operation can be triggered by a disruption of the light barrier. When that happens, firstly a short video sequence is recorded by the *fly-in camera* (further referred to as the *door camera*, *D*), then a longer sequence is recorded by the *ground camera* (further referred to as the *floor camera*, *F*). RFID identification is performed in parallel with the camera recording.

A real design of the application is much more complex though and is discussed on multiple levels – operating systems, libraries and processes/tasks. Its hierarchy is depicted in Figure 17.

4.2.1. Operating Systems

There is a wide selection of operating systems used in embedded. Most of them are *real-time operating systems*, i.e. operating systems meeting *real-time requirements*. Such systems guarantee the response within strict time constraints, often referred to

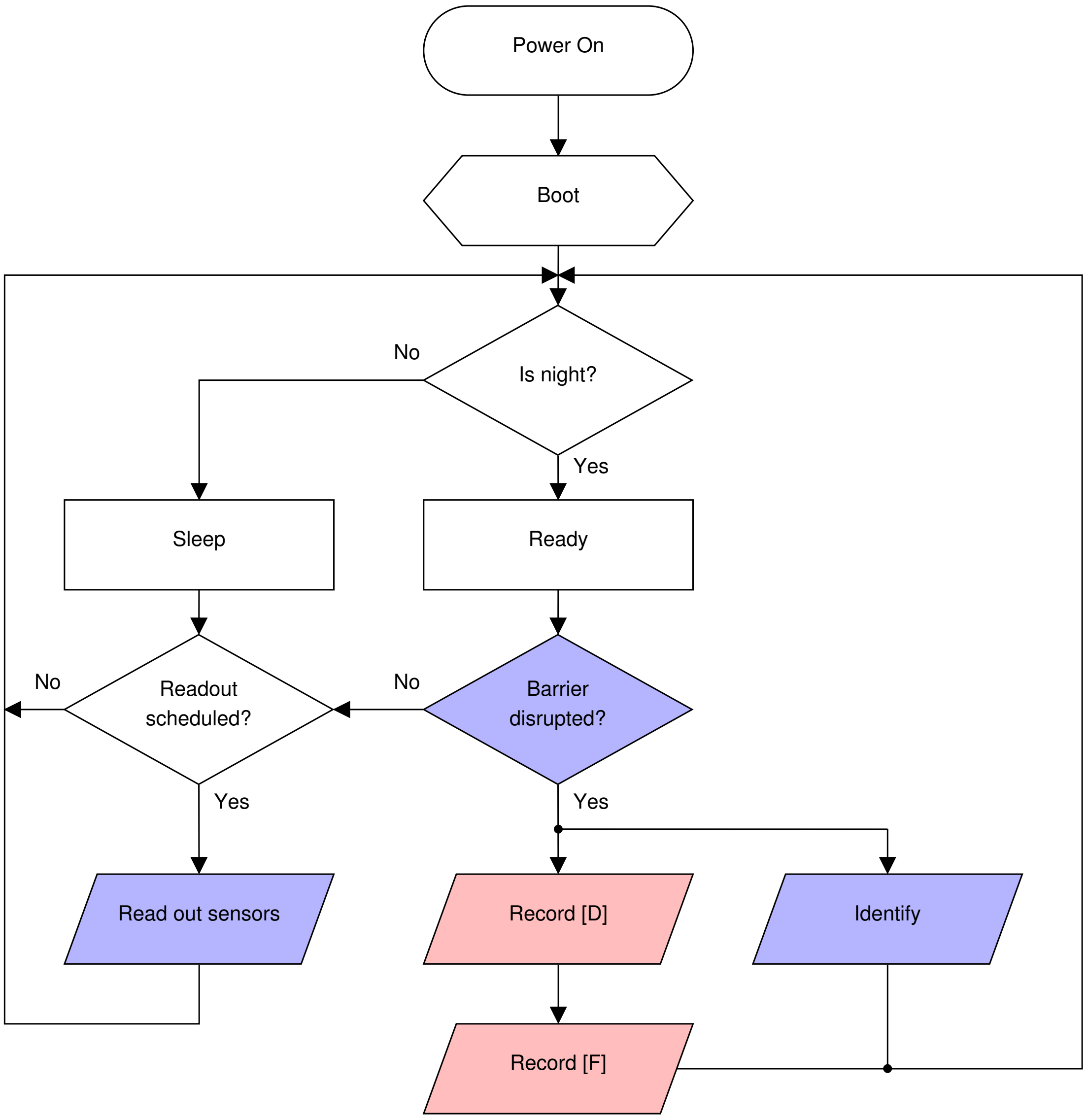


Figure 16. General application flowchart. The blue blocks are executed by the M4 core, the red blocks by the A5 core.

as *deadlines*. Depending on the consequences of missing the deadline, real-time systems are divided into three groups:

- "***Hard:*** *Missing a deadline is a total system failure.*
- ***Firm:*** *Infrequent deadline misses are tolerable, but may degrade the systems quality of service. The usefulness of a result is zero after its deadline.*
- ***Soft:*** *The usefulness of a result degrades after its deadline, thereby degrading the system's quality of service.*" [19]

The Birdhouse application can be categorized as a *soft real-time* system, posing real-time requirements on the delay between the light barrier disruption and start of recording by the *door camera*. The requirements were not defined specifically, but they can be derived from the need to record at least 3 frames of the prey by the *door camera* before it falls on the ground, i.e. out of the camera view. As the prey occurrence takes about 500 ms, the recording must start with respect to this duration and the camera frame rate. From the user point of view, the best would be if the recording started

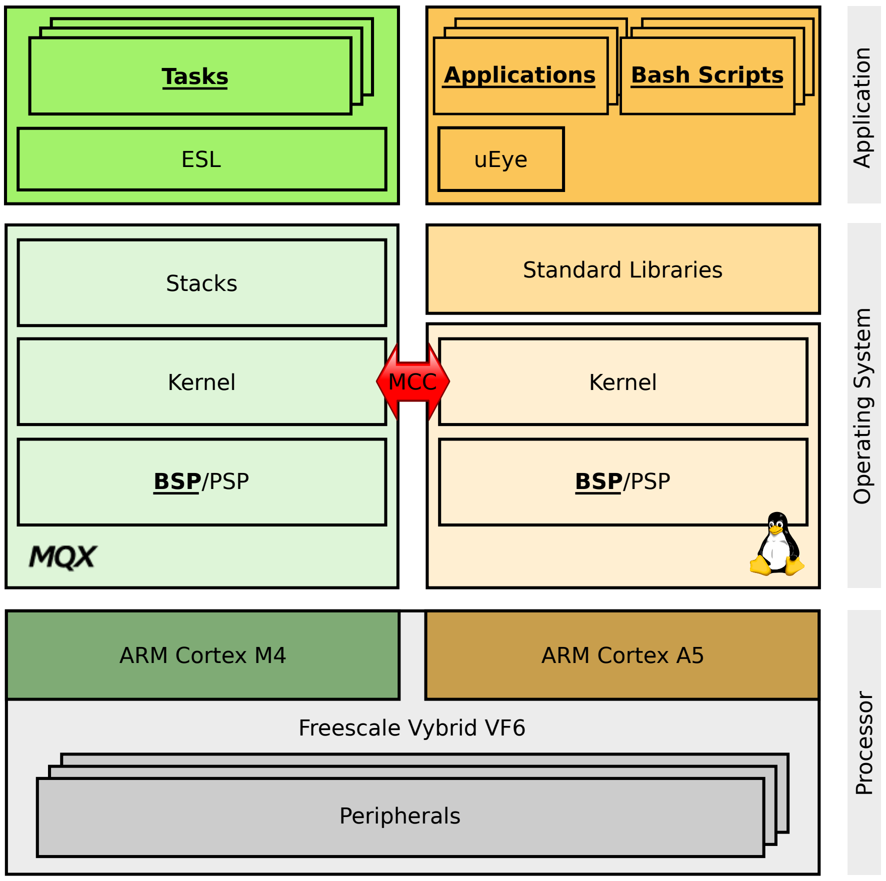


Figure 17. The system software block diagram from the HW/OS point of view. All application specific parts, implemented in terms of this work, are labelled in **underlined bold font**.

"immediately", i.e. the system should minimize the time delay between the disruption event and recording start.

The freedom of selection in this application has been limited from the beginning though. The *uEye library*, needed to access and control the cameras (see 4.2.2), is available only in the binary form for Windows PC and Linux under a limited number of architectures. Use of the latter operating system on the A5 core is hence inevitable.

Analogously, to communicate with the AR4100 WiFi SIP (see Section 4.1.7), an operating system supported by the wifi driver has to be selected. From the sparse list of supported operating systems, Freescale MQX^{TM} (MQX) real-time operating system (RTOS) was picked.

MQX RTOS

Freescale MQX^{TM} is a real-time operating system provided by Freescale Semiconductor, Inc (Freescale). It is *free* to use with all Freescale MCUs and MPUs. It features a lightweight component-based microkernel with a highly customizable architecture, as depicted in Figure 18. It is a multi-platform OS with a minimal footprint of necessary components (*Core*), allowing to be used on most Freescale-based devices. The kernel includes a real-time, priority-based pre-emptive scheduler allowing for real-time multitasking and fast interrupt handling, extensive inter-task communication and synchronization facilities [20].

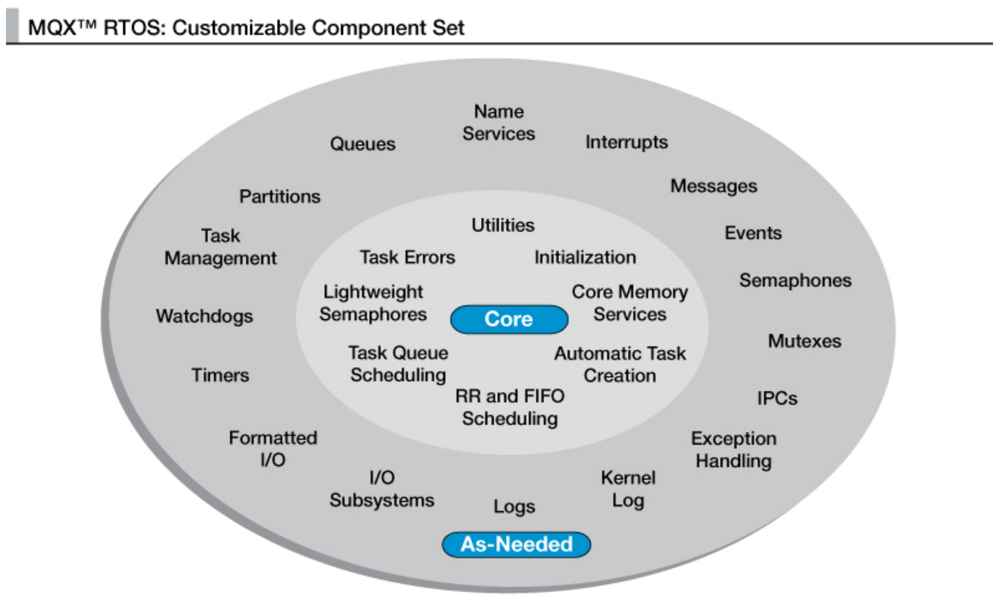


Figure 18. Freescale MQX$^{\text{TM}}$ (MQX) real-time operating system (RTOS) highly customizable microkernel architecture. From [20].

Besides the kernel, MQX contains also Processor Support Packages (PSPs) for all supported platforms, Board Support Packages (BSPs) for various development boards, optional software stacks, services and frameworks (see fig. 19):

- FFS – Flash File System, low-level flash drivers with wear-levelling.
- MCC – Multi-Core Communication library, efficient inter-core MQX-to-MQX or MQX-to-Linux communication subsystem.
- MFS – Embedded MS-DOS File System.
- RTCS – Real-Time Communication Stack, a TCP/IP stack implementation.
- Shell – A lightweight command-line environment.
- USB – Universal Serial Bus host/device stack.

MQX further contains tens of examples and a pretty quality documentation. Together with referential development kits and quite good support, MQX became the best choice of all available operating systems runnable on the M4 core. Also availability of Multi-Core Communication library (MCC) and Elnico Support Library (ESL) is a great advantage, as described in Section 4.2.2.

Timesys Linux OS

Linux is not a real-time operating system by design. There are some Linux kernel modifications or extensions, for example PREEMPT_RT [21], but I have no experiences with these extensions. Since the application belongs to the soft real-time category with no critical impacts in case of failure, this direction was not further considered.

Seeking for a Linux distribution, it was evident that a custom one must be built, as the kernel configuration and BSP must be adjusted according to the custom board. It was logical to choose the *LinuxLink* framework by Timesys Corporation (Timesys) for a bunch of reasons.

First, Timesys is "*a trusted source of embedded Linux*" [22], with deep experience in real-time Linux. They develop *LinuxLink*, a software development framework for configuration, patching, building and maintenance of an open source Linux platform.

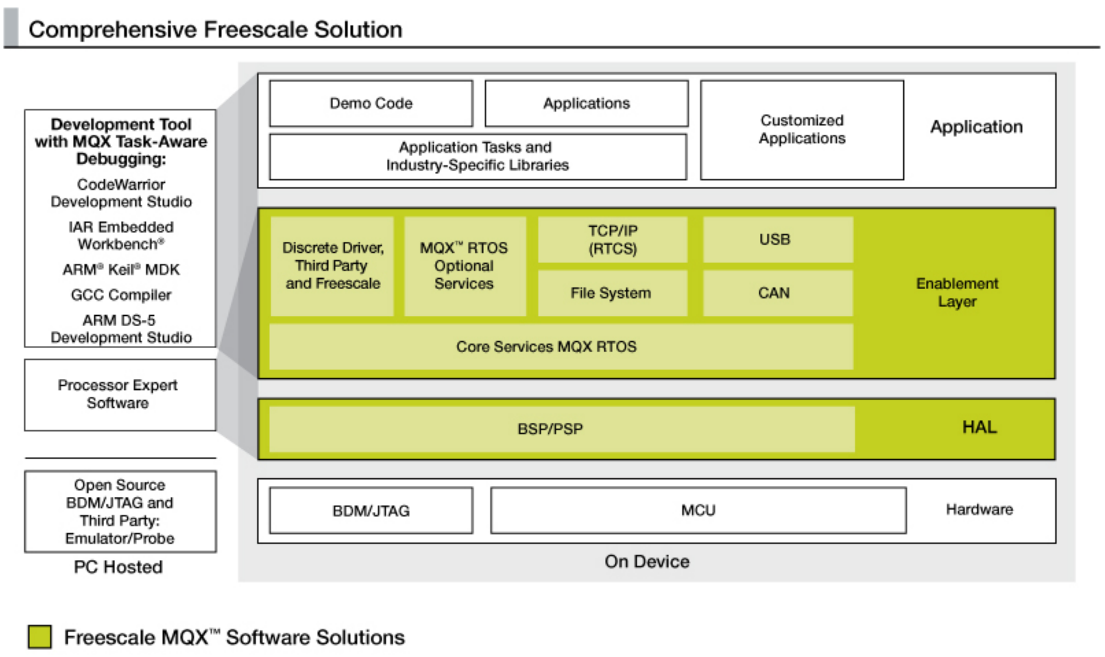

Comprehensive Freescale Solution
Development Tool with MQX Task-Aware Debugging:
CodeWarrior Development Studio
IAR Embedded Workbench®
ARM® Keil® MDK
GCC Compiler
ARM DS-5 Development Studio
Processor Expert Software
Open Source BDM/JTAG and Third Party: Emulator/Probe
PC Hosted
Demo Code
Applications
Application Tasks and Industry-Specific Libraries
Customized Applications
Application
Discrete Driver, Third Party and Freescale
MQX™ RTOS Optional Services
TCP/IP (RTCS)
File System
USB
CAN
Core Services MQX RTOS
Enablement Layer
BSP/PSP
HAL
BDM/JTAG
MCU
Hardware
On Device
Freescale MQX™ Software Solutions

Figure 19. Block diagram of a software solution based on the MQX RTOS. From [20].

"*It includes a Linux kernel, GNU toolchain, packages, libraries and development tools. All Linux platform components and updates are open source and are provided through the LinuxLink Factory custom platform builder*" [23] (see fig. 20 for the typical LinuxLink flow). They also provide documentation and support. They are a partner of Freescale, supplying Linux PSPs for the Freescale's processors and BSPs for their development boards.

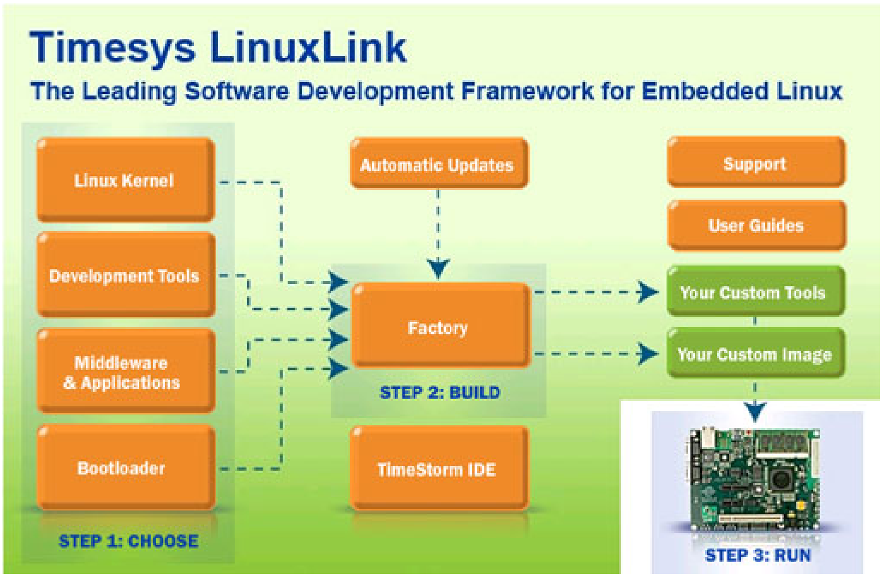


Figure 20. Typical LinuxLink framework flow. From [22].

Second, although LinuxLink is a commercial service, a long-term professional license is granted to every customer who purchased *TWR-VF65GS10* [24], the Vybrid development board by Freescale. Elnico, the manufacturer of the SQM4-VF6-W Vybrid module (Figure 6) and developer of the *BudkaControl* board (design described in Section 4.1.1, realization in 5.1.1), is a LinuxLink licensee and can provide custom Linux configuration and build through this tool.

And finally, Timesys develops and distributes the *mcc-kmod* package [25], a Linux kernel module providing communication with the MQX MCC library (see section 4.2.2). That is, using the Linux by Timesys, we can get well prepared and supported Linux distribution allowing communication with MQX running on the second core.

4.2.2. Libraries

Selection of the essential software libraries used by the application is a fundamental task which has to be done in the software design phase. In this case, uEye, MCC and ESL libraries belong to such category.

uEye Library

uEye is a software library for UI cameras control, provided by their manufacturer, IDS Imaging Development System GmbH. It contains drivers with a daemon process, Application Programming Interface (API), examples and few utilities. It provides the only way to access and control the cameras as they do not comply with common video standards like Video4Linux (V4L).

The library is proprietary and is distributed only in the binary form, the source files are not available. Use of the library (and thus the UI cameras) hence depended on availability of suitable binaries for the ARM® Cortex™-A5 platform. No such library distribution existed. Nevertheless, after some tries it appeared that a distribution for BeagleBoard can be used. BeagleBoard is an open-source hardware computer with an ARM Cortex A8 processor [26]. The A8 and A5 cores have the same architecture ARMv7-A, so they feature the same instruction set [27]. For this reason, the binaries built for BeagleBoard are compatible with the A5 core on Vybrid VF6, even though they are not optimized for use on this MPU. The latest uEye library distribution for BeagleBoard (uEye version 3.90) was downloaded from [28], up-to-date PC binaries and documentation is available from [29].

The library features a C/C++ API, providing a high number of functions, briefly:

- Preparing image capture – camera opening and closing, querying library and camera information, image buffer allocation and freeing.
- Camera configuration – getting and setting camera pixel clock, exposure, gain, gamma, saturation, frame-rate, image preprocessing, ...
- Capturing – capture mode setting, capture control, event handling.
- Storing – single frames loading and saving to the file system.
- External communication – General Purpose Input/Output (GPIO) and flash control, I^2C communication.

MCC Library

The Multi-Core Communication library (MCC) is a subsystem which enables communication of applications running on different cores of multicore processors. Each communication channel consists of two message queues stored in the shared RAM, signalization is realized by interrupts and exclusive access by hardware semaphores. That ensures a lightweight and fast communication with simple blocking/non-blocking send/receive API calls [30].

The library supports MQX and Linux operating systems, allowing for either MQX-to-MQX or MQX-to-Linux communication. It is developed by Freescale and Timesys. In MQX, it is shipped as part of the MQX distribution. In Linux, the library can be fetched from a repository. It operates in the kernel space, being injected to the Linux kernel as the *kmod-mcc* kernel module developed by Timesys.

This communication layer is a fundamental part of the *Birdhouse* project, allowing for dual-core MQX-Linux implementation.

ESL Library

The Elnico Support Library (ESL) is a middleware framework built on top of MQX version 4. It is developed by Elnico as a support software for their Kinetis and Vybrid processor modules. It is a modular, highly configurable multiplatform library, simplifying use of often used functionalities and enabling quick composition of new applications from the library modules as follows:

- "*appctrl – application control mechanisms,*
- *cfg – config files parser and writer,*
- *crc – cyclic redundancy check,*
- *fs – useful filesystem functions,*
- *gpio – GPIO interrupts demultiplexer,*
- *i2c – I2C communication,*
- *log – logging task,*
- *mcfs – virtual multicore filesystem,*
- *nand – NAND flash file system,*
- *rtc – real time controller,*
- *sd – SD card,*
- *spi – SPI bus control,*
- *spimem – SPI memory control,*
- *wifi – Atheros wifi control.*" [31]

Use of the library can significantly simplify and accelerate the target application development, reducing the application code size as Figure 21 illustrates.

Most of the library modules are used in this project, namely *appctrl*, *cfg*, *gpio*, *i2c*, *log*, *mcfs*, *rtc* and *wifi*.

appctrl is a simple module implementing task *eslAppCtrl*. Its purpose is to start all the other application tasks and control their run. In the version used in the *Birdhouse* application (1.004, not publicly available at the time of writing this document), its function is limited to simply starting all the other tasks in a defined order.

cfg is an implementation of a very simple configuration files processor. Configuration files are needed to keep the user settings, e.g. camera exposure times.

gpio realizes a simple interrupt demultiplexer. On Vybrid, there is only one interrupt vector for each GPIO port. When there are more then one GPIOs from the same port used, the application needs to check on which pin from the port the interrupt originated. That is done by this module.

i2c module is a set of functions for accessing the I^{2}C peripheral, enforcing mutual access to each channel. The I^{2}C peripheral is used to communicate with the sensors on the *BudkaLTS* board (see Section 4.1.6).

log implements logging functions and a task responsible for writing the log messages to a defined location (a UART standard output and/or a file on a file system). It collects logging messages from both the library and the application.

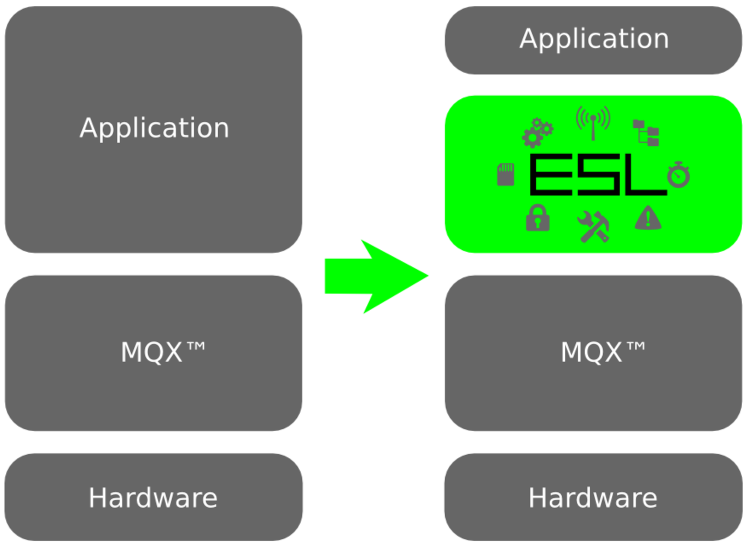


Figure 21. Elnico Support Library middleware diagram. From [31].

mcfs is a virtual multi-core file system used to access a Linux file system from MQX. It installs a file system into MQX and communicates using MCC with a Linux daemon running on the second core and actually executing the read/write commands. Since the whole dual-core system disposes of only one non-volatile memory storage (Secure Digital (SD) card), it has to be shared by both cores, i.e. by both operating systems. One solution would be to use hardware semaphores to synchronize access to the device, which would probably require modifications in the Linux kernel. Multi-Core File System (MCFS) gives an alternative way to share the medium as described previously in this paragraph, and is used in this application for all MQX file operations.

rtc is a simple set of functions for date/time operations, e.g. generating time stamps for log and other purposes.

wifi is a complex module containing the driver for the AR4100 Atheros wifi SIP. On the top of the driver and the MQX TCP/IP stack, access point and managed modes are implemented. This module can be used for the WiFi human-machine interface.

4.2.3. Processes and Tasks

From the processes and tasks point of view, the application gets pretty complicated. The overall processes/tasks diagram is depicted in Figure 22.

In MQX, the whole application is formed of a single executable binary, containing the OS kernel, drivers and user program. Individual subprograms are implemented similarly to threads, but are called *tasks* and play the role of *processes* in the Linux/Windows terminology. For this reason, MQX tasks and Linux processes in Figure 22 are shown on the same level of abstraction. They are described in the following subsections.

appmgr

appmgr is the name used for two executable entities – an MQX task *appmgr*^{M} and a Linux process *appmgr*^{L}. They form two sides of the main core of the *Birdhouse* application. They are the only executable entities which perform the inter-core communication (if not counting the MCFS subsystem), forming the application's backbone.

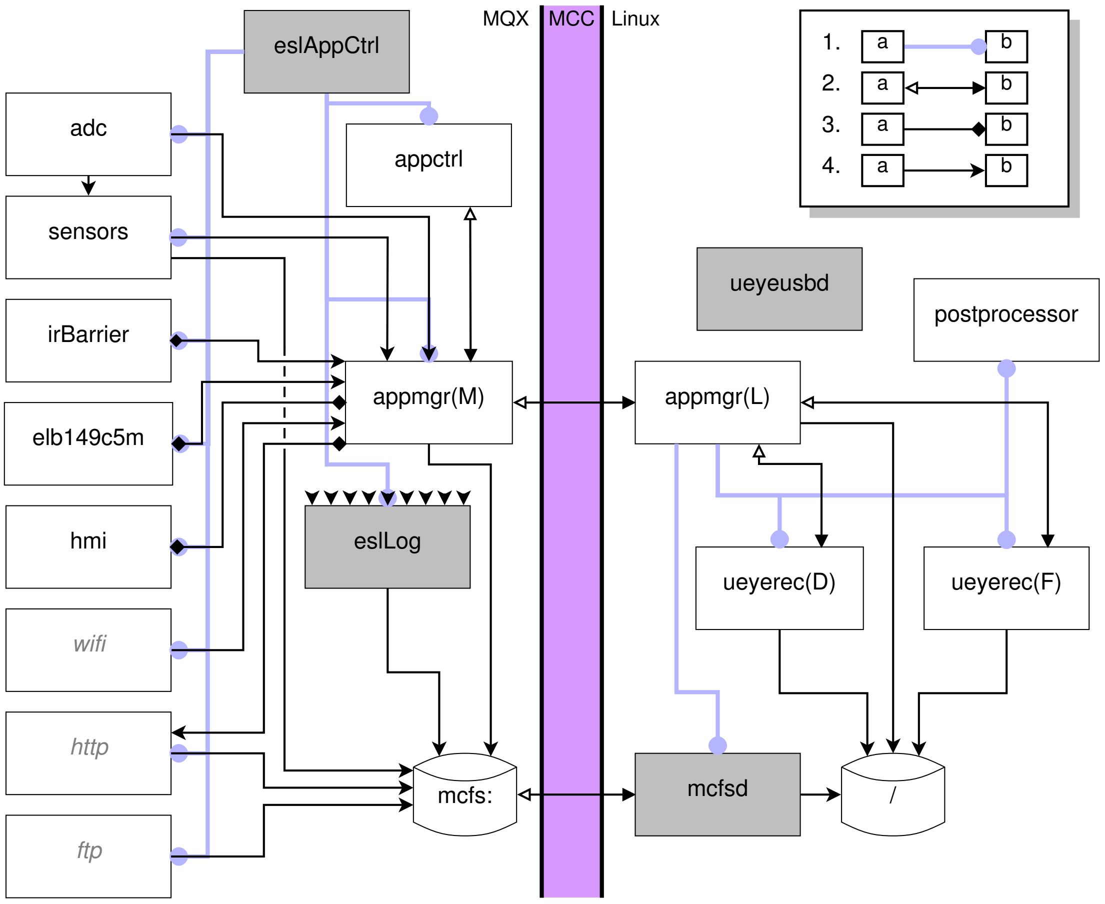


Figure 22. Birdhouse application processes/tasks communication diagram. In MQX, each block represents one task. In Linux, each block represents one process. Grey blocks represent third-party tasks/processes. Tasks labelled in grey italics were not implemented. Legend: **1.** *a* starts *b*. **2.** Client-server communication, *a* being a client of *b*. **3.** *a* controls *b*. **4.** *a* sends data to *b*.

appmgr^M plays the superior role in the communication based on the client-server model, *appmgr*^{M} being the client and *appmgr*^{L} being the server. The communication protocol for the three most important operations is defined in Table 1. The client always starts the communication by sending a message of given *type*. Each message can further contain *iParam*, *iParam2*, *iParam3* and *uParam* parameters. *WAKEUP*, *SLEEP*, *RECORD*, *RECORD_FINISH* and *ACK* message types and *MCC_OK* and *MCC_ERROR* return codes are defined.

appmgr^M is basically an event processor which after initialization cycles in an endless loop, as depicted in Figure 23. There are three main event types: *SLEEP*, *WAKEUP* and *RECORD*. After an event is detected, appropriate operation is executed. Should any of the operations fail, the whole processor is reset immediately and the application must start again from the beginning, recovering from the failure state.

SLEEP and *WAKEUP* events are triggered by a periodic timer. They switch the application to the *READY* mode at predefined evening time, and to the *SLEEP* mode at predefined morning time. The subsequent operations are depicted in Figures 24 and 25. Both operations are similar – *appmgr*^{M} sends corresponding message to *appmgr*^{L}, waits for reply and powers on/off the RFID and infrared light barrier (IRBAR) devices (through *elb149c5m* and *irBarrier* tasks).

Message	Protocol Description
WAKEUP	The server powers-up the USBs and starts ueyerec for both the door and floor camera. It replies with ACK where iParam is set to the operation result – MCC_OK on success, MCC_ERROR if something failed. In the case of failure, uParam contains additional information about which camera experienced problems. The server remains in the READY mode anyway. It is responsibility of the client to take appropriate action to fix the state.
SLEEP	The server stops ueyerec for both the door and floor camera and powers-down the USBs. It replies with ACK where iParam is set to the operation result – MCC_OK on success, MCC_ERROR if something failed. uParam then contains additional information about which camera experienced problems.
RECORD	To create a record of two video sequences and accompanying data, client sends a RECORD message with data triplet [interier temperature], [exterier temperature], [exterier light] stored in iParam, iParam2, iParam3. If the server is ready (i.e. it is in the READY mode and not busy), it immediately replies by ACK with iParam set to MCC_OK and starts recording the video. In a short time period, the client sends a RECORD_FINISH message, with iParam set to MCC_OK and uParam set to detected RFID code, or with iParam set to MCC_ERROR if no RFID code was detected. The server replies after finishing the recording job by ACK with iParam set to either MCC_OK or MCC_ERROR depending on the operation result. If the server is not ready when the RECORD message is received, it replies by ACK with iParam set to MCC_ERROR and the transaction ends, client does not send more messages.

Table 1. *appmgr* inter-core client-server communication protocol. The communication is always initiated by sending a message of type in the left column from *appmgr*^{M} to *appmgr*^{L}.

The *SET_READY* operation is more complicated by taking several trials before giving up, as the remote operation labelled as *A5_SET_READY* is not fully reliable due to USB issues. That is not a pleasant solution but it is acceptable, as this operation is not time-critical.

The *RECORD* event is triggered by disruption of IRBAR, handled by the *irBarrier* task, and is only valid when the system is in the *READY* mode. The operation has two steps, as shown in Figure 26. First *appmgr*^{L} is notified about the event so the camera recording starts. *appmgr*^{L} replies immediately so *appmgr*^{M} can continue operation. It waits for a predefined delay and then retrieves last scanned RFID code from the *elb149c5m* task. Depending on the age of the code (as every code is equipped with a timestamp), it is used or thrown away. Then a *RECORD_FINISH* message is sent to *appmgr*^{L} and execution stops until a reply is received. It is responsibility of *appmgr*^{L} to store all the records to the permanent storage.

appmgr^L is the main process on the Linux side of the application. It firstly starts the *mcfsd* process needed for the MCFS file system, and then it enters the infinite message loop, as depicted on a flowchart in Figure 27. It is an interlink between MQX (*appmgr*^{M}) and the recording processes, instances of *ueyerec*. It plays a role of a *server* in the MCC communication (with *appmgr*^{M}) and a *client* in the inter-process communication (IPC) with *ueyerec*.

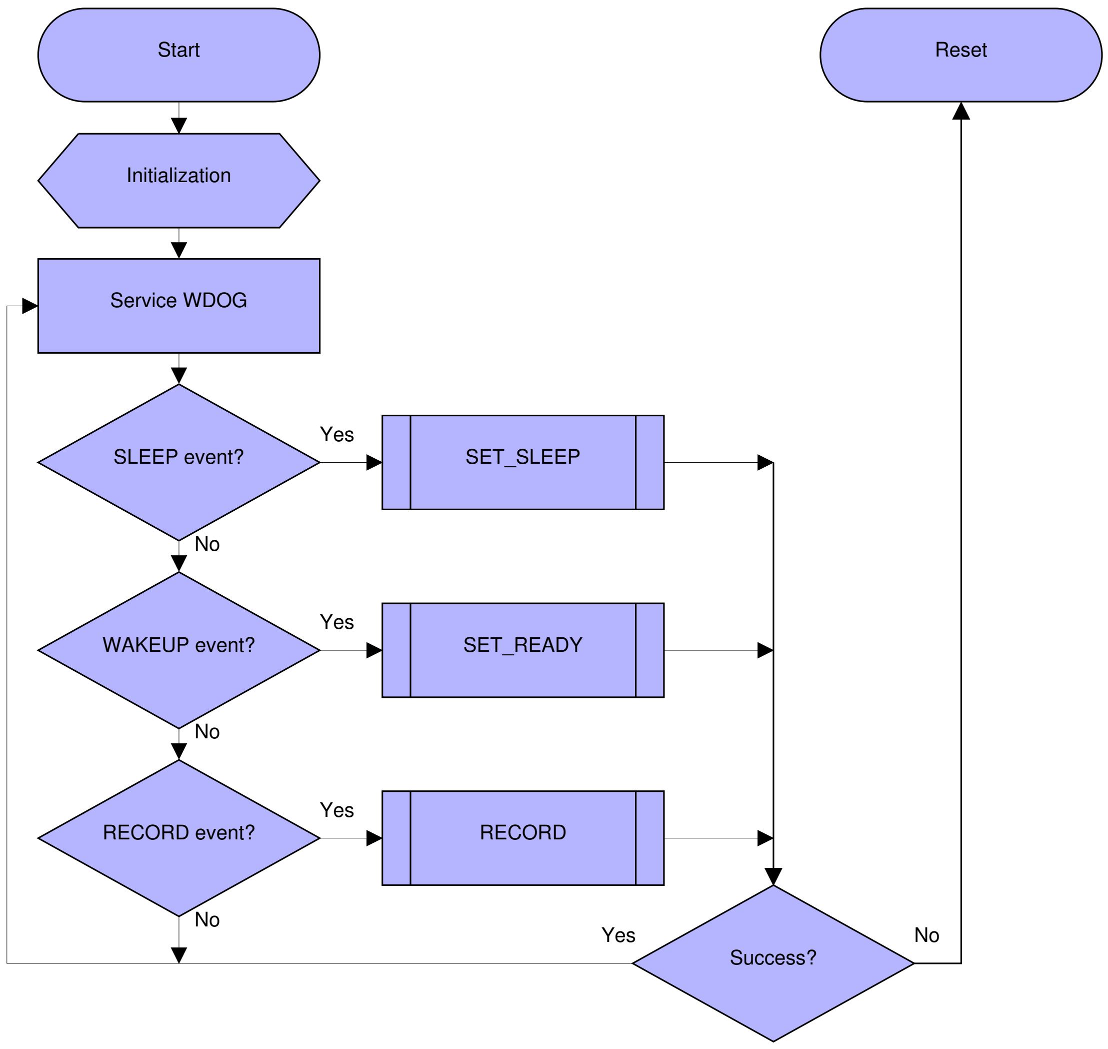


Figure 23. *appmgr*^{M} task flowchart. *SET_SLEEP*, *SET_READY* and *RECORD* operations are depicted in Figures 24, 25 and 26.

The infinite loop realizes the *server* role for *appmgr*^{M}. When a message is received, *appmgr*^{L} executes appropriate operation including a *client* communication with *ueyerec*. These operations are depicted in Figures 28 and 29.

In *A5_SET_READY* operation (Figure 28), *appmgr*^{L} powers on both USB channels and tries to run two instances of *ueyerec*, each for one camera. This operation, labelled as *START_UEYEREC*, first involves forking and running a new process – instance of *ueyerec*. This process is given an inter-process communication (IPC) queue identifier (ID) of *appmgr*^{L}. To allow for bidirectional communication, *appmgr*^{L} needs to know IPC queue ID of the new task - that is done during a three-step handshake illustrated in Figure 30. First *ueyerec* sends a *HANDSHAKE1* message with ID of its IPC queue. *appmgr*^{L} replies by *HANDSHAKE2* message with system process ID of the *ueyerec* process, which replies by an empty *HANDSHAKE3* message, playing a role of simple acknowledge (ACK). By that, the IPC communication between these two tasks is established. *appmgr*^{L} then instructs *ueyerec* to get to the *Ready* mode by opening, activating and configuring the camera (messages *OPEN*, *ACTIVATE*, *SET_EXPOSURE* and *SET_GAIN*). Full collection of used IPC messages and their parameters is listed in Table 2.

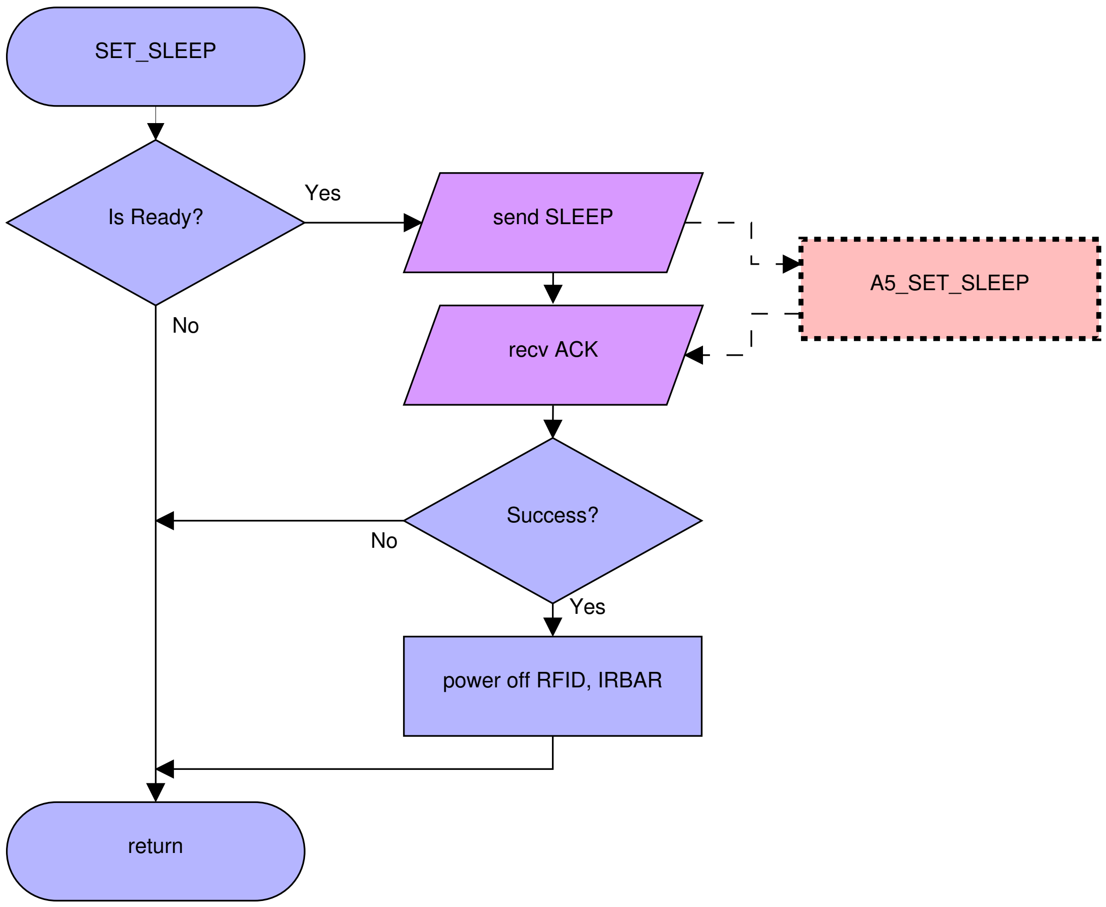


Figure 24. *SET_SLEEP* operation flowchart, executed by *appmgr*^{M}. Violet blocks represent MCC communication. The red block is illustration of corresponding A5 operation (*appmgr*^{L}).

In *A5_SET_SLEEP* operation (Figure 28), *appmgr*^{L} stops both instances of *ueyerec* and powers off both USB channels. Stopping the *ueyerec* processes involves a sequence of IPC messages (*DEACTIVATE*, *CLOSE*, *QUIT*), followed by a forced kill of the process if it does not terminate as requested.

A5_RECORD_START operation (Figure 29) simply checks that *appmgr*^{L} is ready for recording. *A5_RECORD_FINISH* (Figure 29) is also trivial, it only outputs data received from *appmgr*^{M} (sensor data and RFID code) to a file.

More complicated is the *A5_RECORD* operation (Figure 29). It first commands the *ueyerec* process handling the *door camera* (*ueyerec*^{D}) to record a video sequence of preset parameters (duration, framerate), and then it does the same for the *ueyerec* process handling the *floor camera* (*ueyerec*^{F}) with different parameters.

The IPC communication hidden behind this "command" is following: *appmgr*^{L} sends a *LIVE* message with requested duration and frame-rate of the video record to be captured, *ueyerec* replies by *SUCCESS* message, *appmgr*^{L} sends a text message with output filenames format, *ueyerec* records the video sequence and replies by *SUCCESS* message.

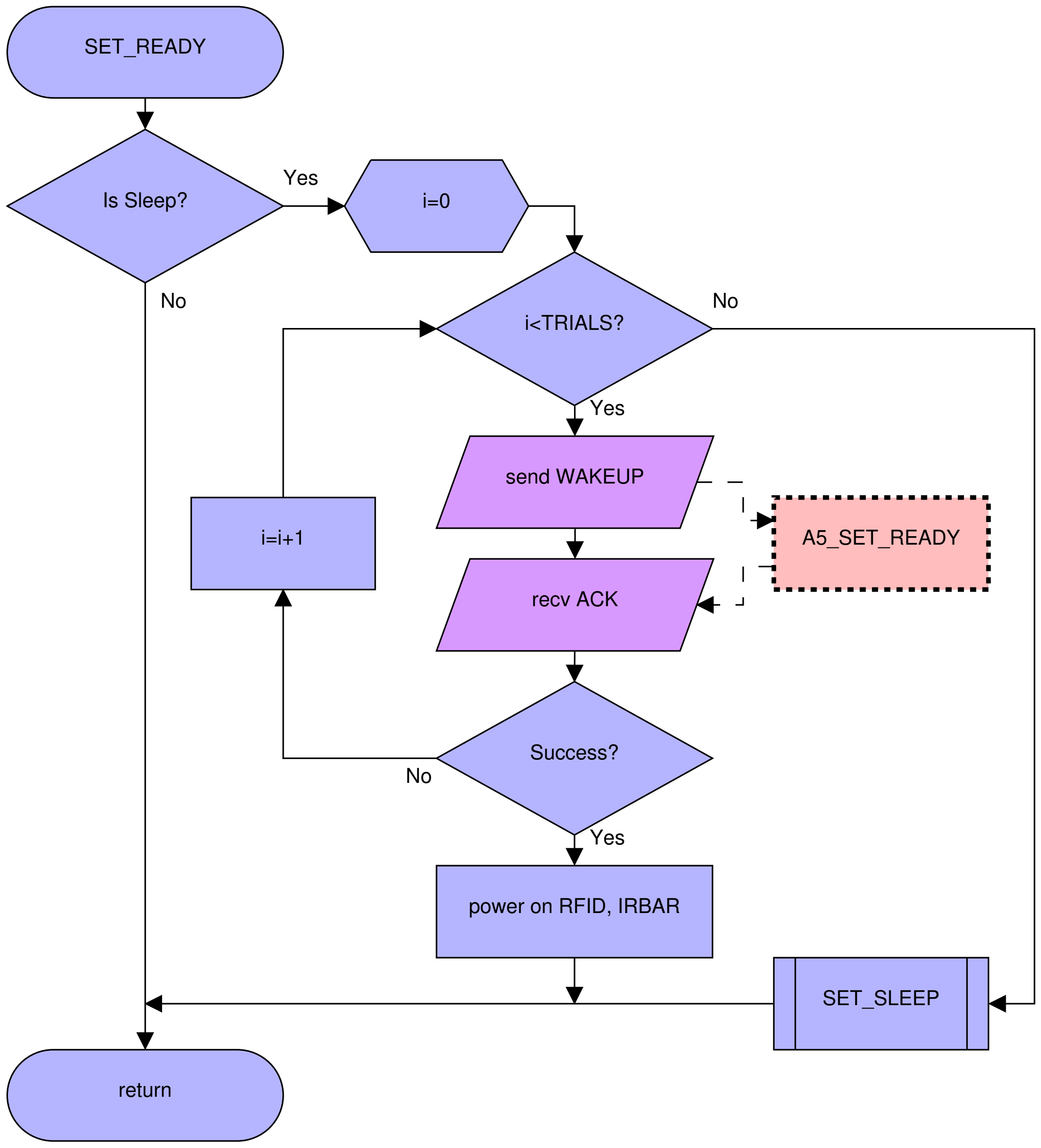


Figure 25. *SET_READY* operation flowchart, executed by *appmgr*^{M}. Violet blocks represent MCC communication. The red block is illustration of corresponding A5 operation (*appmgr*^{L}).

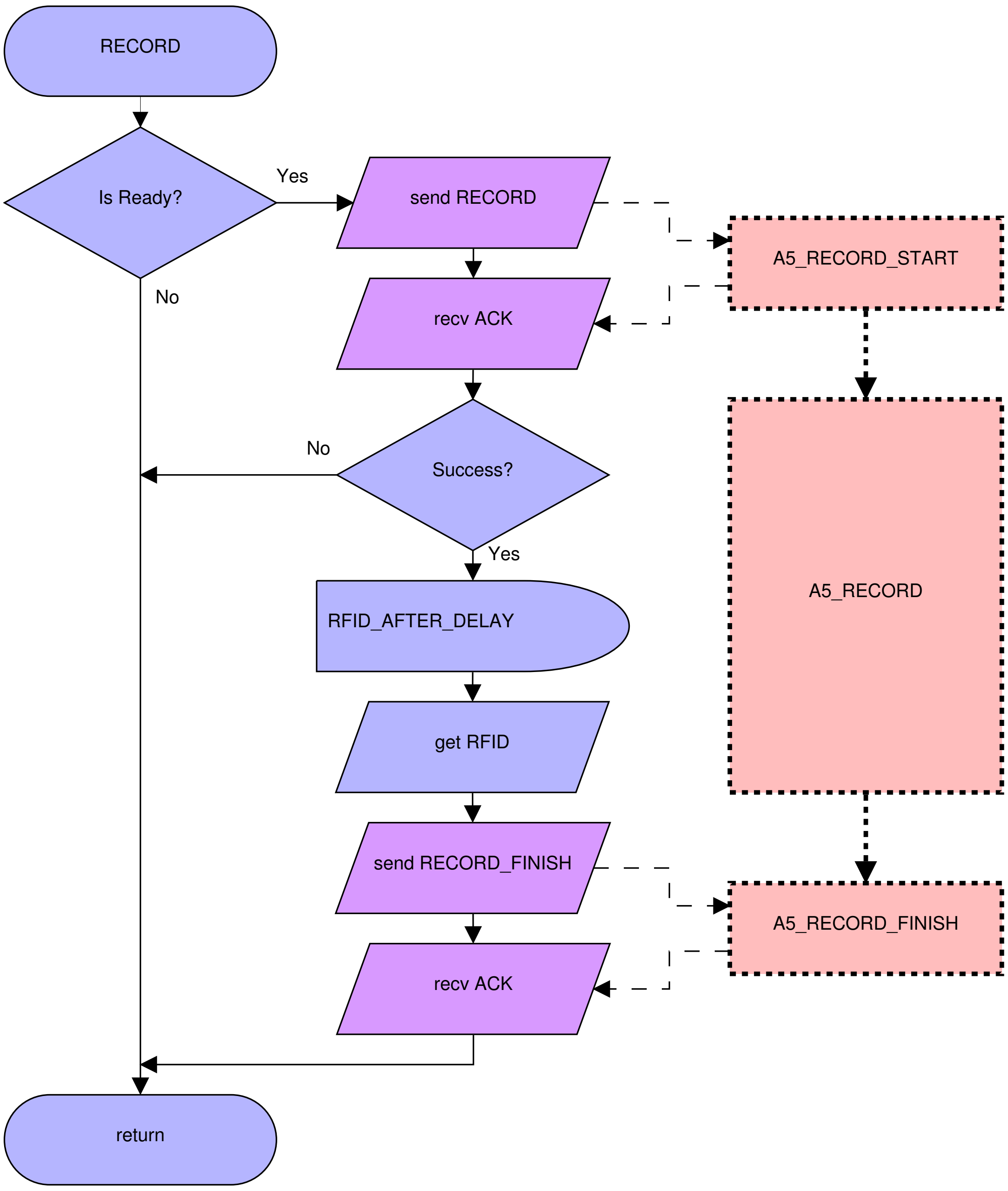


Figure 26. *RECORD* operation flowchart, executed by $appmgr^M$. Violet blocks represent MCC communication. The red blocks are illustration of corresponding A5 operations ($appmgr^L$).

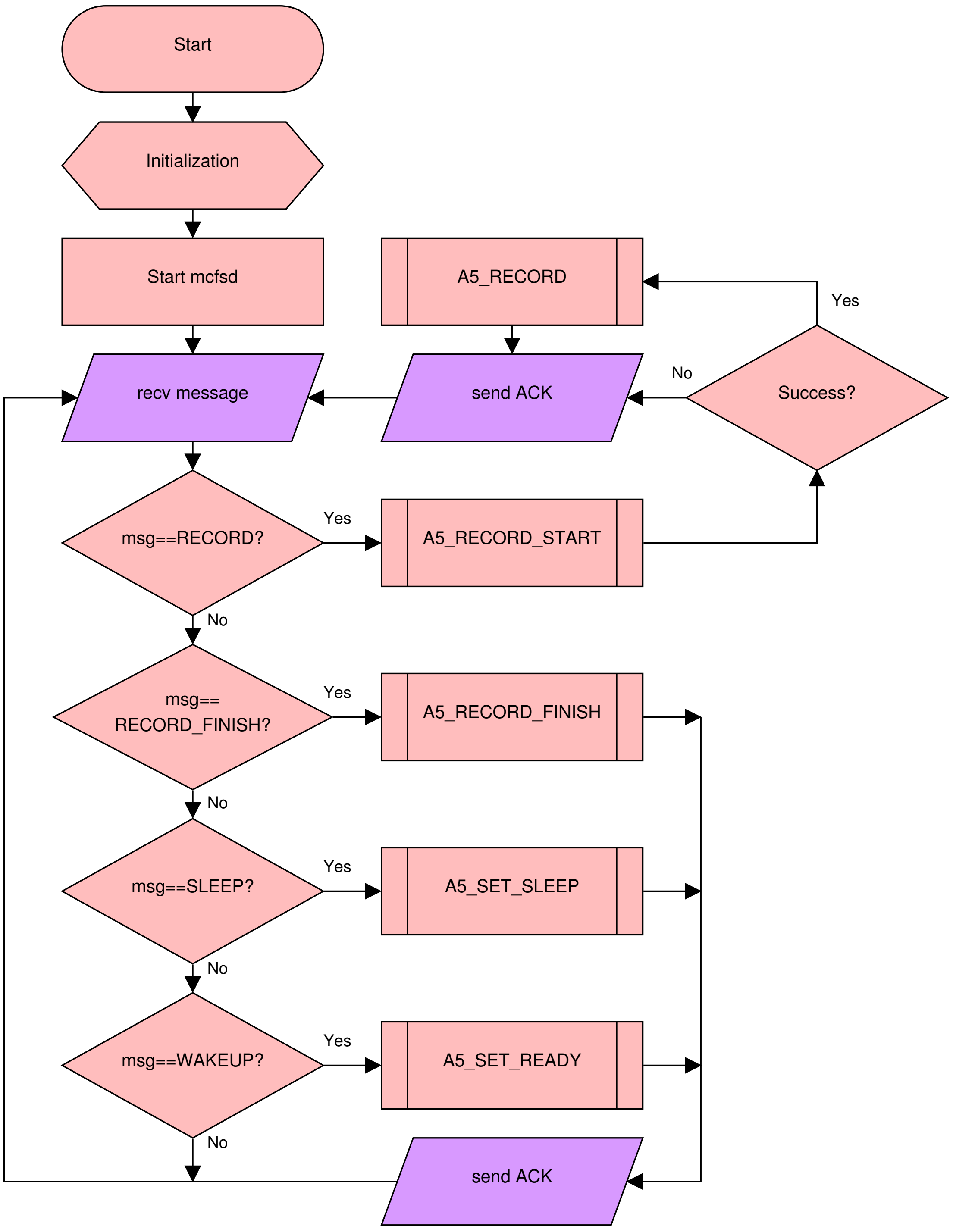


Figure 27. *appmgr*^{L} task flowchart. Violet blocks represent MCC communication. *A5_SET_SLEEP*, *A5_SET_READY*, *A5_RECORD_START*, *A5_RECORD* and *A5_RECORD_FINISH* operations are depicted in Figures 28 and 29.

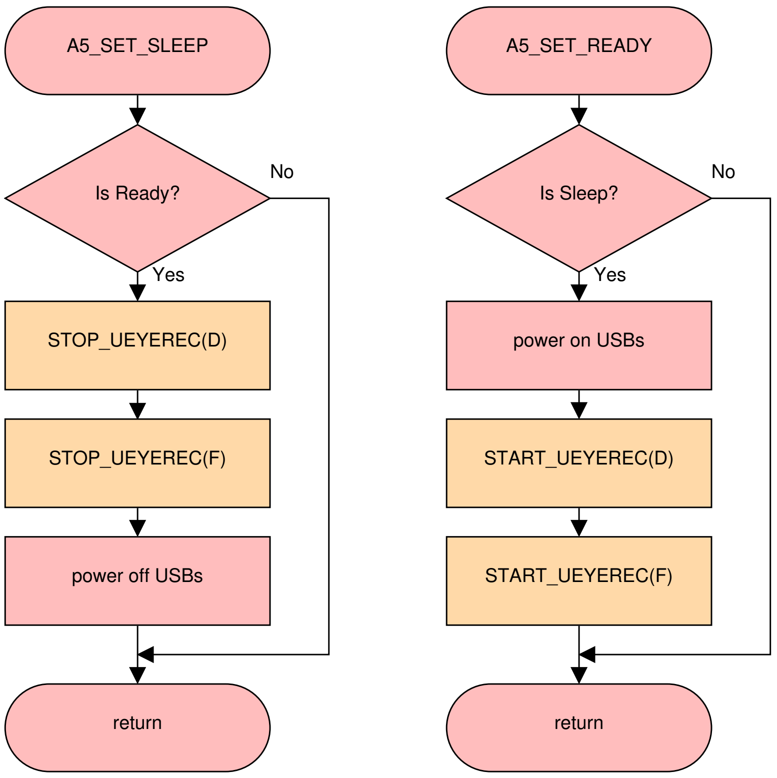


Figure 28. *A5_SET_SLEEP* and *A5_SET_READY* operations, executed by *appmgr*^{L}. Orange blocks involve IPC communication with *ueyerec*.

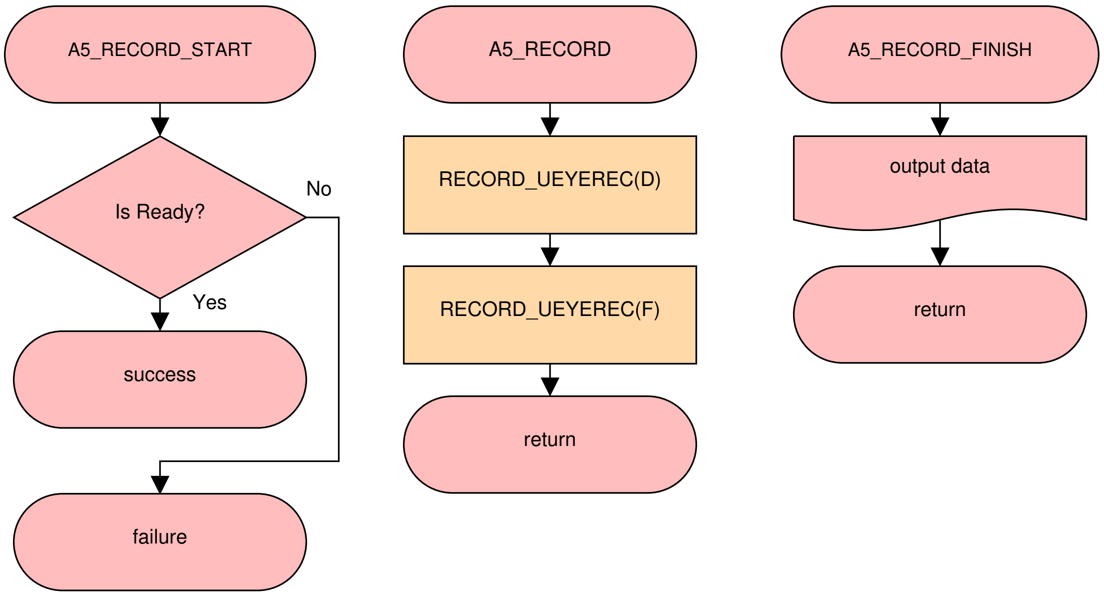


Figure 29. *A5_RECORD_START*, *A5_RECORD* and *A5_RECORD_FINISH* operations, executed by *appmgr*^{L}. Orange blocks involve IPC communication with *ueyerec*.

Message	Parameters	Description
QUIT	–	Quit the application.
OPEN	–	Open the camera.
CLOSE	–	Close the camera.
ACTIVATE	–	Wakeup the camera from standby.
DEACTIVATE	–	Sleep the camera to standby.
LIVE	duration, framerate	Capture a video of specified parameters.
SET_EXPOSURE	exposure	Set camera exposure time.
SET_GAIN	gain	Set camera chip gain.
HANDSHAKE1	IPC queue ID	First handshake message (sent by server).
HANDSHAKE2	process ID	Second handshake message (sent by client).
HANDSHAKE3	–	Last handshake message (sent by server).
SUCCESS	–	Operation success (sent by server).
FAILURE	–	Operation failure (sent by server).

Table 2. Inter-process communication messages between *appmgr*^{L} and *ueyerec* processes.

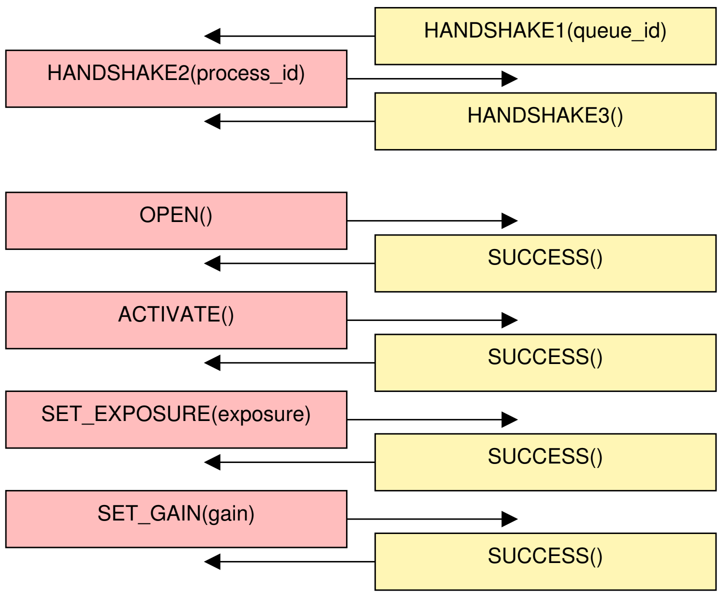


Figure 30. Inter-process protocol illustration on case of operation *START_UEYEREC*. Yellow messages are sent from *ueyerec* to *appmgr*^{L}, the red ones in the opposite direction.

ueyerec

ueyerec (the name comes from *UI recorder*) is the only program designed to access and control the cameras (or better to say the camera; two program instances are needed to control two cameras). It serves as a server for *appmgr*^{L}. It provides commands to open, configure and close a camera, and to take a snapshot or record a sequence of video frames.

The program again cycles in a message queue, as depicted in Figure 31. Messages are received first from the *user interface (UI)*, second from the connected *camera*, and third from a *periodic timer*.

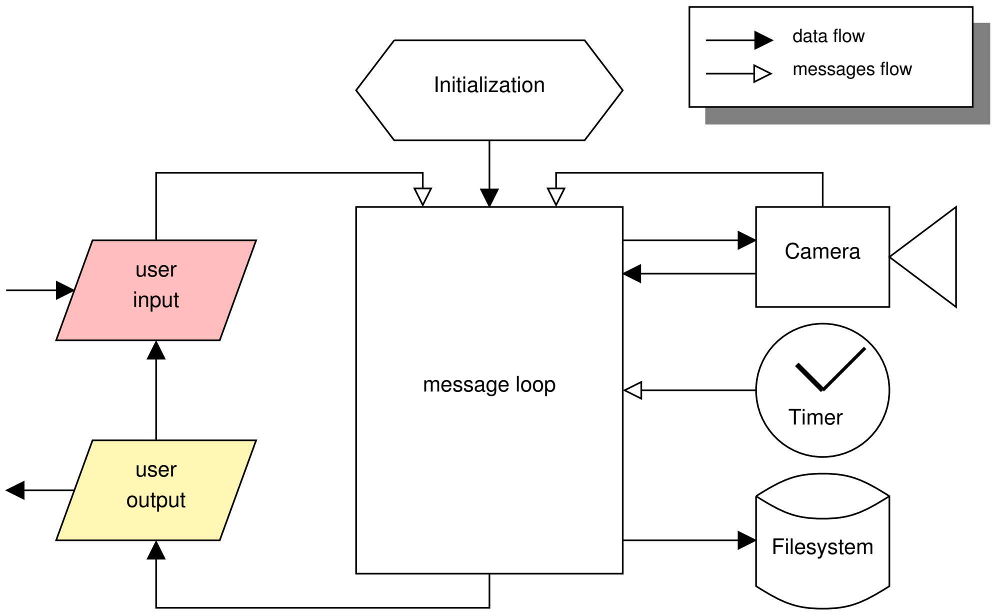


Figure 31. Simplified *ueyerec* functionality diagram illustrating *data* and *messages* flow inside the program.

On the target device, *ueyerec UI* stands for the IPC communication with *appmgr*^{L}, being a source of commands corresponding to the camera control messages from Table 2.

The *camera* produces several types of events, which are then translated to messages handled by the message loop. In the used camera mode (*Software Trigger mode*, see Figure 32), the considerable events are *TRIGGER* and *FRAME* events. The *TRIGGER* event is emitted when the camera is ready for the next frame capture, i.e. when the last frame was already captured and transferred, but not preprocessed by the uEye library API. Last frame preprocessing (generally e.g. color conversion) and new frame capturing can be done in parallel, as both operations run on different hardware. When the frame is also preprocessed by the API and is ready for the application processing, the *FRAME* event is triggered.

The events need to be translated by separate threads to the messages recognized by the main message queue. When the corresponding *FRAME* message is received, *ueyerec* simply stores the captured frame to the file system as an image file, as the uEye library under Linux does not provide direct output in a video format (e.g. Audio Video Interleave (AVI)). New frame capture is initiated after the file has been saved, since this sequential approach saves memory (only one image buffer is needed) and prevents the code from potential bugs, while providing high enough frame-rate (for this application).

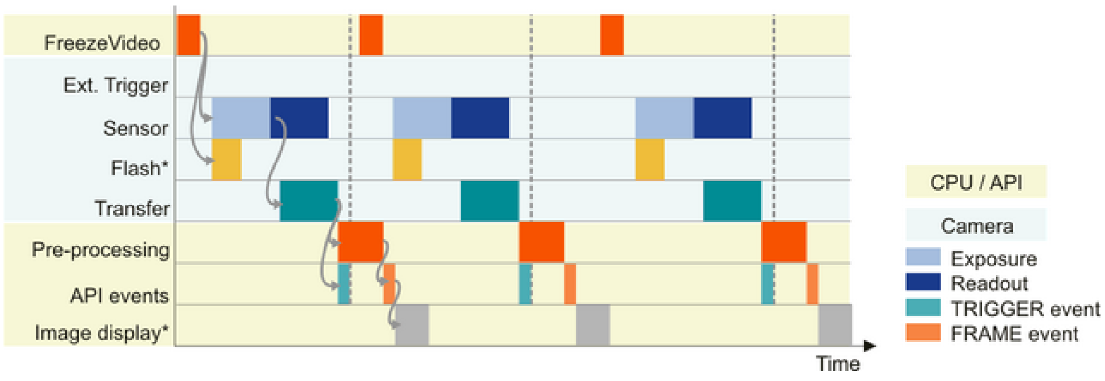


Figure 32. uEye camera *software trigger mode* flow diagram. From [32].

To allow for capturing frames with a requested frame-rate, new capture cannot be initiated right after the application is ready for it, but it needs to wait for a synchronization message from a *periodic timer*. The timer sends two types of messages – first the periodic frame ticks, and second the *end of capture* message to ensure proper capture length.

When the whole image sequence is complete, it needs to be encoded to the video format. That is done asynchronously using an external script labelled as *postprocessor* (see Section 5.2). The script is run by *appmgr*^{L}.

ueyeusbd

ueyeusbd is a Linux daemon (i.e. a background process) responsible for the system to recognize an attached USB camera, and perform all background work needed for its correct operation. The program is part of the uEye library.

mcfsd

mcfsd is a Linux daemon playing the role of server in the MCFS subsystem. It receives file operation requests from the MQX application via MCC library, and performs the operations on the local file system. It is a third-party program delivered as a part of ESL library. More information at [31].

eslAppCtrl

eslAppCtrl is the only automatically started MQX application task. It comes from the ESL library. Its ultimate goal is to start and *control run* of all application tasks, i.e. realize a software watchdog. Currently it only starts all application tasks.

appctrl

appctrl is an MQX task which supplies *eslAppCtrl* in the tasks control function. Anyway, it currently controls only *appmgr*^{M} which is the main task of the application and every critical failure of any subsystem earlier or later projects to failure of *appmgr*^{M}.

The *appctrl* task cycles in an infinite event loop, receiving events from *appmgr*^{M} and a *periodic timer* with a shorter period then the expiration delay of the hardware watchdog. In every cycle, it services the HW watchdog and increments a counter. When the counter exceeds predefined threshold, the task resets the MCU. To avoid hardware reset, the counter must be reset to zero by receiving the event from *appmgr*^{M} (notice the *Service WDOG* block in Figure 23), effectively realizing SW watchdog of that task.

irBarrier

irBarrier is an MQX task intended to control the *BudkaIRBar* board. That involves generation of a periodic signal for the light transmitter, and evaluation of input from the receiver. The periodic output signal of required frequency 38 kHz is generated by the FlexTimer (FTM) peripheral configured to the PWM mode. When the barrier disruption is detected, *irBarrier* signalizes it to *appmgr*^{M} by setting the *RECORD* event. The task also provides an interface for disabling and enabling the IRBAR, so it can be powered off in the *SLEEP* mode to save the power resource.

elb149c5m

elb149c5m is an MQX task that performs readouts from the ELB149C5M RFID reader. It simply reads the data written to the Universal Asynchronous Receiver/Transmitter (UART) peripheral and checks the checksum. The EM4200 code contains 10 ASCII data characters (representing a hexadecimal code) followed by a 2-bytes long checksum - cumulative XOR of the previous 5 subsequent pairs of bytes (see an example in [14]). If the read checksum equals the computed checksum, the code is correct and its decimal representation (ignoring the first 2 HEX characters) is stored to a variable together with current timestamp. This is read by *appmgr*^{M} during the *RECORD* operation (see Figure 26) and – if the code was scanned near the time of the *RECORD* event – stored together with the recorded video data. The task also provides an interface for disabling and enabling the reader for the same reasons as the *irBarrier* task.

adc

adc is an MQX task which measures the power supply voltage using the MCU's A/D converter (ADC) peripheral. The purpose of the task is to inform about the battery state and – if the voltage is too low – power off the system. The value, calculated as a sliding average of last 60 measurements, is reported to the *sensors* task which integrates it into its output.

sensors

sensors is an MQX task which periodically aggregates data from the temperature and light sensors (I^2C communication with the *BudkaLTS* board) and battery voltage from the *adc* task, and writes them to the MCFS file system.

hmi

hmi is an MQX task serving as a simple testing interface. It presents the internal application state via a LED blinking with different frequencies, and it controls the *appmgr*^{M} task via a set of debug buttons. These devices have little to no use in the final application though, as they are inaccessible in practice.

wifi, httpd, ftpd

wifi task is intended to initialize, configure and control an access point of a wireless network, realizing the user interface of the system. *httpd* and *ftpd* tasks are meant to operate the Hypertext Transfer Protocol (HTTP) and File Transfer Protocol (FTP) servers, accessible through the wireless network. Due to a collision in DMA operation, caused probably by use of the same channel by both the MQX wifi driver and Linux kernel, the Wi-Fi functionality is only roughly prepared, but could not be completed. The problem must be fixed on the level of either ESL library or Linux kernel.

eslLog

eslLog is an ESL task processing all logging messages from the application and the ESL library itself. Its purpose is to serialize the messages and write them to a predefined medium (standard output and/or a file). It provides a simple interface for logging messages of multiple severities (debug, information, warning and error).

5. Implementation

The system implementation was determined by its design, and was also already partially described in Chapter 4, since *design* and *implementation* of such a completely new and complex system go hand in hand. This chapter describes mainly the *products* of the implementation, that is resulting hardware and software equipment and its practical use.

5.1. Hardware

All the commercial hardware selected in Section 4.1 was procured, all the custom hardware was developed and manufactured by Elnico s.r.o. This section presents the resulting products.

5.1.1. Control Board

The *BudkaControl* control board was realized as a simple two-layer printed circuit board (PCB). See its schematics in Appendix B.1, routings and silkscreens in Appendix C.1. Labelled photo of the board is shown in Figure 33.

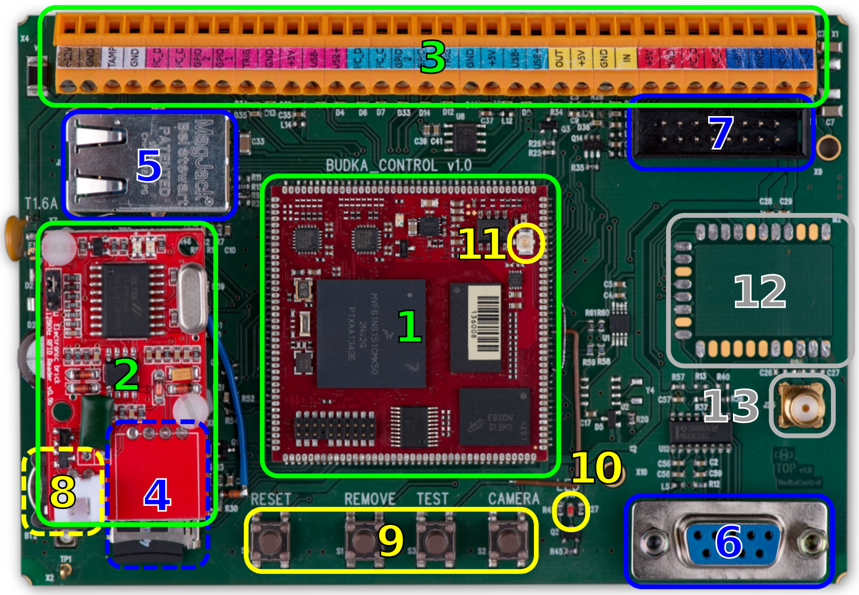


Figure 33. Realization of the *BudkaControl* board. **1.** SQM4-VF6-W processor module. **2.** ELB149C5M RFID reader with antenna connector. **3.** Terminal strip for power source and peripheral boards connection. **4.** MicroSD card slot. **5.** RJ45 Ethernet connector. **6.** RS-232 debug port serial connector. **7.** Expansion connector. **8.** 3V battery holder. **9.** Reset and testing buttons. **10.** Status LED. **11.** U.FL Male WiFi antenna connector. **12.** RTX4100 WiFi module footprint (not placed). **13.** WiFi antenna connector for RTX4100 module (not used).

	Clamp	Peripheral	Function
🟫	J12-2	Power Supply	+12V
🟫	J12-1	Power Supply	GND
▨	J18-2	Tamper Detect	TAMPER1
▨	J18-1	Tamper Detect	GND
🟪	J6-2	Camera 1	*I2C_D*
🟪	J6-1	Camera 1	*I2C_C*
🟪	J14-2	Camera 1	*GPIO2*
🟪	J14-1	Camera 1	*GPIO1*
🟪	J20-2	Camera 1	*TRIGGER*
🟪	J20-1	Camera 1	GND
🟪	J19-2	Camera 1	+5V
🟪	J19-1	Camera 1	USB-
🟪	J9-2	Camera 1	USB+
🟦	J9-1	Camera 0	*I2C_D*
🟦	J7-2	Camera 0	*I2C_C*
🟦	J7-1	Camera 0	*GPIO2*
🟦	J1-2	Camera 0	*GPIO1*
🟦	J1-1	Camera 0	*TRIGGER*
🟦	J11-2	Camera 0	GND
🟦	J11-1	Camera 0	+5V
🟦	J10-2	Camera 0	USB-
🟦	J10-1	Camera 0	USB+
🟨	J16-2	Light Barrier	IRLEDFREQ
🟨	J16-1	Light Barrier	+5V
🟨	J21-2	Light Barrier	GND
🟨	J21-1	Light Barrier	IRDETECT
🟥	J27-2	Sensors Internal	+5V
🟥	J27-1	Sensors Internal	GND
🟥	J26-2	Sensors Internal	I2C_D
🟥	J26-1	Sensors Internal	I2C_C
🟦	J29-2	Sensors External	+5V
🟦	J29-1	Sensors External	GND
🟦	J17-2	Sensors External	I2C_D
🟦	J17-1	Sensors External	I2C_C

Table 3. Terminal strip peripherals and cables assignments. The left column background colours correspond to peripheral colour markings on the terminal strip. Background colours of individual cells in the *Function* column correspond to colours of respective cables. Signals in gray italics are not used.

The board basically expands all needed peripherals of the *SQM4-VF6-W* module, which is mounted in the center of the board (**1**). The ELB149C5M RFID reader module (**2**) is located over the base board, which it is fixed to using spacers. Under the RFID module, there is placed a MicroSD card slot (**3**) and a 3V battery needed for powering the on-chip Real-time Clock (RTC) peripheral when the power source is detached. Next to the RFID reader, RJ45 Ethernet connector is placed (**5**). For connecting all the peripheral boards, terminal strip (**3**) is used. Cable assignments according to their colours is listed in Table 3. Next to the terminal strip, there is one expansion connector (**7**) with additional GPIOs, SPI and few more signals. It is currently unused though.

For development and debug purposes, there is one serial connector (**6**) attached to an RS-232 debug port, one reset and three debug/testing buttons (**9**) and a low-power LED for signalizing the application status.

To implement the WiFi interface, there is a prepared space for the *RTX4100* WiFi module (**12**) and an antenna connector (**13**). This was meant as a fall-back solution in case of problems with the *AR4100P* WiFi SIP placed on the *SQM4-VF6-W* module. An the end, it was not even tested due to a very low throughput, as it is designed for extremely low-power applications [33]. The *AR4100P* WiFi SIP on *SQM4-VF6-W* module will be used instead when the collision of ESL with Linux kernel is solved, as described in 4.2.3. U.FL Male connector (**11**) for connecting the WiFi antenna is prepared on the processor module.

The board dimensions are designed to fit in the *ELBOX 171x121x55 transp.* installation box with protection IP65 [34] by Enika.cz s.r.o. (Enika). Photographs of the board covered and installed in the nest-box can be found in Appendix D.

5.1.2. Camera and Lighting

The *BudkaLighting* board was realized as a simple two-layer PCB directly connected to the *UI-1541LE* camera. See its schematics in Appendix B.2, routings and silkscreens in Appendix C.2. The photo of the board with highlighted board items is shown in Figure 34.

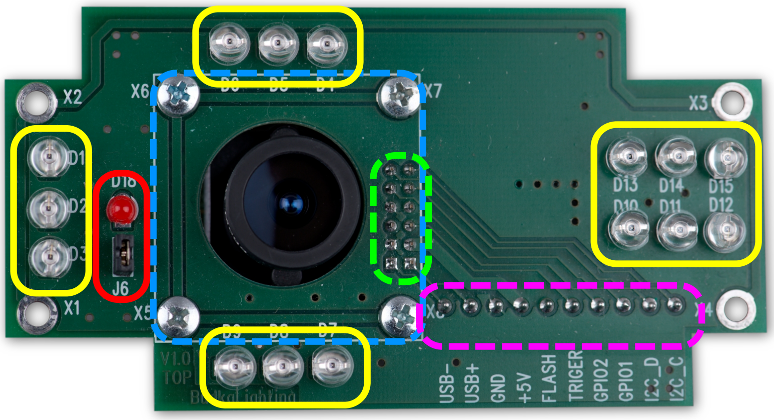


Figure 34. Realization of the *BudkaLighting* board, with highlighted board items (description in the text). Dashed lines mark components placed from the other side.

The board implements the IR flash as five parallel sets of three *TSHG5510* IR LEDs (*areas highlighted by yellow rectangles*). There is also one additional red LED used for testing purposes – it can be easily turned off by removing the jumper (*red area*). The camera (*blue area*) is placed on the other side of the board, connected by its *I/O connector* (see [35]), directly facing the board's connector (*green area*), and fixed on spacers. The *USB+* and *USB-* signals are not present in the camera *I/O connector*, but there is an additional USB connector used for that purpose.

The camera is connected only to the *BudkaLighting* board, which is connected to the *BudkaControl* board by a USB cable attached to the terminal strip placed on the bottom side of the *BudkaLighting* board (*violet area*). Hence only *USB-*, *USB+*, *GND* and *+5V* are used, being connected to the corresponding signals on the *BudkaControl* board by cables coloured as in Table 3. Remaining signals are not used. The lighting is controlled automatically by the camera (if configured appropriately).

Dimensions of the board together with the camera are designed to fit in the *ELBOX 115x65x40 transp.* installation box with protection IP65 [36] by Enika. Photographs of the board covered and installed in the nest-box can be found in Appendix D.

5.1.3. Light Barrier

The *BudkaIRBar* board was realized as a simple two-layer PCB of the mirrored "U" shape. Its schematics is presented in Appendix B.3, routings and silkscreens in Appendix C.3. Photo of the board with illustrated light beam and its direction is shown in Figure 35. Realistic photograph can be found in Appendix D.

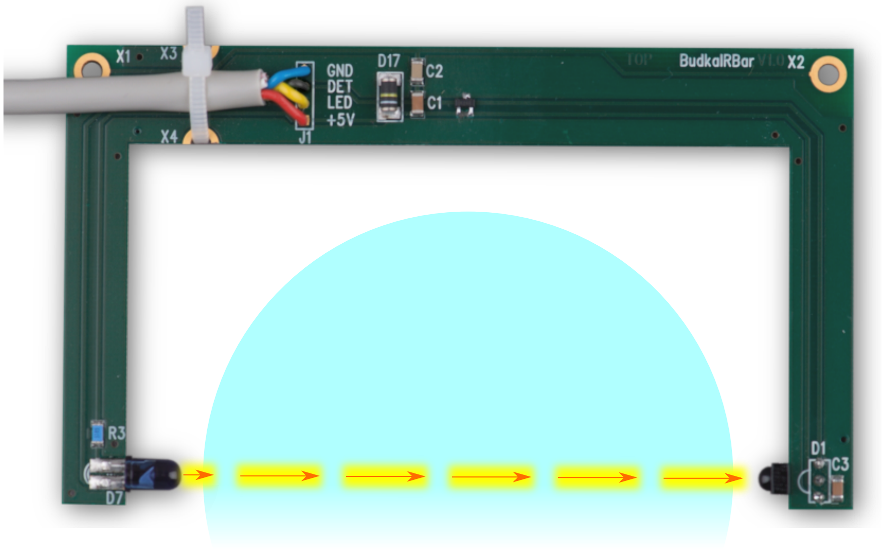


Figure 35. Realization of the *BudkaIRBar* board, with highlighted light beam and its direction.

The board is connected to the *BudkaControl* board by a standard four-wire cable, with individual wires coloured according to the colour scheme in Table 3. The *BudkaIRBar* board is not covered in any box, it is meant to be fixed directly in a groove in the wood by two screws and covered by a wooden and metal plate. The whole board is varnished for better endurance against the weather conditions.

5.1.4. Temperature and Light Sensors

The *BudkaLTS* board was realized as a tiny PCB, common for both variants (with and without the light sensor). See its schematics in Appendix B.4, routings and silkscreens in Appendix C.4. The illustration photo of the variant *with* light sensor, with labelled assembled parts is depicted in Figure 36.

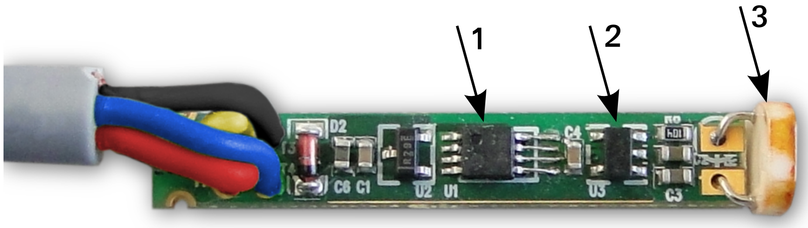


Figure 36. Realization of the *BudkaLTS* board, variant with the light sensor. **1.** Temperature sensor *MCP9804*. **2.** A/D converter *MCP3221*. **3.** Photocell *VT83N2*.

The board is produced in two instances. Both instances are placed by a *MCP9804* I^{2}C digital temperature sensor with $\pm 0.25°C$ typical accuracy and $-40°C$ to $+125°C$

operation range [17]. The exterior sensors board is also placed by a *MCP3221* low power I^2C 12-bit A/D converter [37], measuring the voltage on the photocell *VT83N2* [38].

The board is designed to fit in a capsule of a pen or marker, and isolated by silicone rubber, as visible on the realistic photographs in Appendix D, Figures 62 and 63. It is attached to the terminal strip on *BudkaControl* board by a four-wire cable according to the colour scheme in Table 3.

5.1.5. RFID Reader

The RFID reader selected during the system design (*ELB149C5M*, Section 4.1.4) is mounted directly to the control board, as described in Section 5.1.1. The external antenna was manufactured by Libor Hofmann [39] following the dimensions from Figure 13. Its photo is shown in Appendix D in Figure 64. The antenna is connected by a two-wire cable to the original white connector on the reader module.

5.1.6. Cover Tamper Button

As an additional feature, the terminal strip on the control board contains two signals for *Tamper Detect*. It is used to connect a button serving as a detector of the battery door being open/closed. The *TAMPER1* signal is connected to the input of *Tamper* peripheral on the Vybrid MCU. When the main power supply is not provided, that peripheral is powered by the 3V backup battery so it can detect unauthorized access even in the case of disconnected/discharged battery. This functionality has not been implemented in the software yet though.

5.2. Software

The *Birdhouse* application software has been implemented following the design described in Section 5.2. Some implementation details and application use guidelines will be described here.

5.2.1. Toolchain

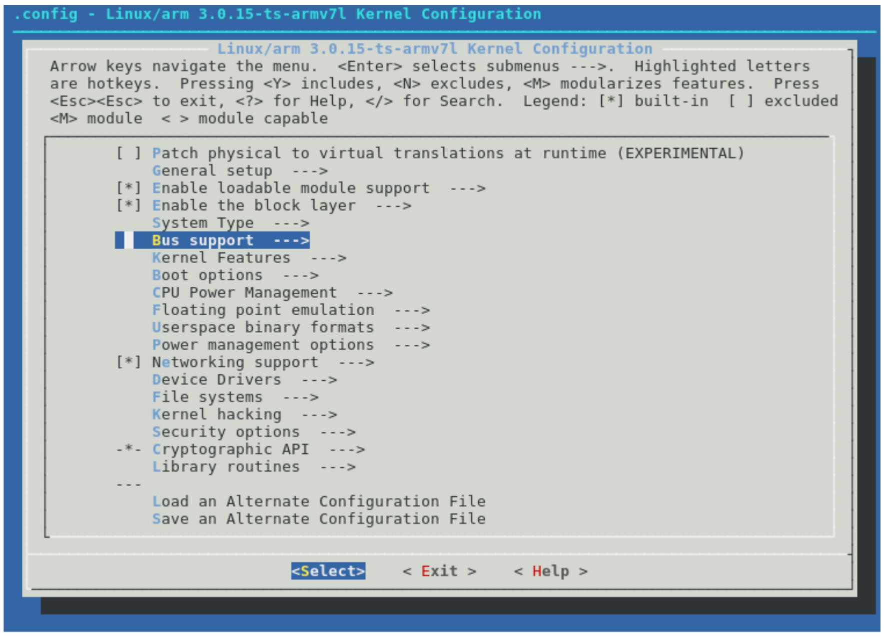
Toolchain is a set of tools and libraries used to develop the application. The *Birdhouse* application, being run on two different systems in parallel, has been developed under two toolchains – GNU for Linux application development and IAR for MQX application development.

Linux

For implementation of the Linux side of the application, LinuxLink Factory (Factory) build system has been used. It enriches the GNU toolchain [40] by a few (omissible) tools – *advice engine* and *upgrade engine* (more at [22]). GNU toolchain is a collection of programming tools produced by the GNU Project, licensed under a sort of GNU General Public License (GPL) licenses (typically Lesser General Public License (LGPL) – the software can be used for free even for proprietary commercial projects).

The GNU toolchain consists of tens of tools. The key tools are *GNU make* (build automation tool), *GNU Compiler Collection (GCC)* (C and C++ compilers), *GNU binutils* (linker, assembler), *GNU build system* (autotools) and *GNU Debugger (GDB)* (code debugging tool).

The Linux kernel, several tools and the whole distribution can be configured using the *menuconfig* tool, accessible as a Makefile target. It provides a semi-graphical interface for easy interactive configuration (see Figure 37) of *.config* files, containing complex information about packages to be built and their options, together with dependency resolution, simple search and help.



```
.config - Linux/arm 3.0.15-ts-armv7l Kernel Configuration
                     Linux/arm 3.0.15-ts-armv7l Kernel Configuration
  Arrow keys navigate the menu.  <Enter> selects submenus --->.  Highlighted letters
  are hotkeys.  Pressing <Y> includes, <N> excludes, <M> modularizes features.  Press
  <Esc><Esc> to exit, <?> for Help, </> for Search.  Legend: [*] built-in  [ ] excluded
  <M> module  < > module capable

        [ ] Patch physical to virtual translations at runtime (EXPERIMENTAL)
            General setup  --->
        [*] Enable loadable module support  --->
        [*] Enable the block layer  --->
            System Type  --->
            Bus support  --->
            Kernel Features  --->
            Boot options  --->
            CPU Power Management  --->
            Floating point emulation  --->
            Userspace binary formats  --->
            Power management options  --->
        [*] Networking support  --->
            Device Drivers  --->
            File systems  --->
            Kernel hacking  --->
            Security options  --->
        -*- Cryptographic API  --->
            Library routines  --->
        ---
            Load an Alternate Configuration File
            Save an Alternate Configuration File

                    <Select>    < Exit >    < Help >
```

Figure 37. Screenshot of the *menuconfig* utility when configuring the Linux kernel.

To run *menuconfig* for the Linux kernel, `make kernel-menuconfig` command-line command is used, while command `make menuconfig` is used to run *menuconfig* on so-called *Workorder* (in Timesys terminology), i.e. the Linux distribution configuration.

Concerning the kernel and workorder configuration, there is an official distribution available for the *TWR-VF65GS10* [24] Vybrid development board by Freescale in the Factory, as already described in Section 4.2.1. Elnico sells a development kit for their SQM4 modules – the *SQM4 EasyBoard Development Kit* (EasyBoard) [41] – derived from the Freescale Tower development platform, being highly compatible with that board. Elnico provides modification of the official Vybrid distribution with some BSP changes and patches for EasyBoard (e.g. support for two USB Host devices, needed for our application).

BudkaControl board has been developed to have the same BSP as EasyBoard, allowing to use the Elnico modification of the Factory workorder without need to make any changes in the Linux kernel.

To sum up, Linux kernel version 3.0 was used, configured and patched for the Vybrid platform. Its source files including the configuration file can be found on accompanying DVD in directory *linux_sdk/kernel-source/* (see Appendix A).

The Factory workorder configuration was reused, some changes were made though. For example, configuration of *BusyBox*[1] was modified to include *tcpsvd* and *ftpd*, tools needed to run a minimal FTP server for the remote data access over Ethernet.

[1]A minimum bash-like processor. It is an “all-in-one” application implementing hundreds of stripped-down versions of standard command-line utilities, optimized for embedded environments.

Some libraries had to be added to the toolchain, too, for example *libconfig* (configuration files handling library) or – of course – *libueye* (UI cameras API). The full workorder configuration is stored in the *linux_sdk/.config* configuration file (see Appendix A).

MQX

While all the development of the Linux side of the application was done under Linux host operating system, all MQX development was done under Microsoft™ Windows® OS (Windows). *IAR Embedded Workbench* toolchain by *IAR Systems* was used. It is a tool suite for C/C++ development for 8-, 16-, and 32-bit MCUs, including C/C++ compiler, assembler, linker and debugger, optimized for embedded applications including RTOS plug-ins built in an integrated development environment (IDE). *JTAG* interface connected through the *j-Trace* debug probe (by *Segger*) was used for debugging.

All these expensive professional tools, which provide powerful embedded development instruments and produce high-quality outputs, were made available by Elnico.

The 'story' about the MQX BSP is similar to the one of Linux. The *TWR-VF65GS10* BSP is an official part of MQX, distributed together with it in one archive. EasyBoard BSP was derived from the *TWR-VF65GS10* BSP and is available from Elnico. In addition, because *BudkaControl* was designed to be compatible with EasyBoard, its BSP was used for the *Birdhouse* application.

The MQX applications are built the way that the MQX operating system is first configured for the application and pre-built to a set of libraries, containing different components of the system. These are then linked together with the object files of the application into a single executable file, which is then downloaded and run on the device. This library distribution is a part of the project and can be found on the accompanying DVD in *src/birdhouse/libmqx/* directory (see Appendix A).

Similarly to MQX, the ESL library is configured and pre-built to project-specific libraries, which are linked together with the application in a single binary. The ESL library distribution, including the configuration file and binary, is located in *src/birdhouse/libesl/* directory on the accompanying DVD.

5.2.2. Application

This section describes some implementation details about the application startup and recording.

Startup

Standard real-time embedded application is typically a single binary burned directly into the MCU FLASH memory or another type of a non-volatile on-chip Read-Only Memory (ROM), which is directly accessed and executed by the processor. This is also the case of MQX in general. Different approach is taken with Linux though, as the *linux* kernel is too big to fit in the internal memories, and many programmes being run under Linux are even bigger.

For this reason, both *Linux kernel* and *Linux applications* need to be first loaded to the Random Access Memory (RAM) from where they are executed. *Linux kernel* needs to be loaded first, which is done by a bootloader – *U-Boot* in our case. It is a small application which could be written into the on-chip ROM memory, but it is typically stored on a data storage.

In our application, U-Boot is loaded from the MicroSD card. The U-Boot binary is written directly to the SD card memory address `0x400` at a place of no partition[2]. The Vybrid MCU is implicitly configured to load the program from this location.

When U-Boot starts, it initializes the main peripherals (e.g. memories) and mounts the file system on the first SD card partition (named *KERNEL*). Linux kernel binary is stored there – file *uImage-3.0-ts-armv7l* (see directory *linux_sdk/* on the DVD and Appendix A). This file is loaded into the memory and executed by the primary core – A5 (the secondary core – M4 – was not initialized yet and its clock is off).

One of first steps of the Linux boot is to mount the Root File System (RFS) located on the second SD card partition. It contains all files needed to start and run the system, including the application data. During boot, *system init scripts* from the */etc/init.d/* directory are sequentially executed, with respect to their alphabetical order (all scripts beginning with the *S* character). These scripts start services needed for the system run, for example they install kernel modules and run network services. The original init scripts generated by Factory can be found in *<DVD>/linux_sdk/rfs/rootfs.tar.gz*. Custom application scripts are located in *<DVD>/sdcard/rfs_overlay/etc/init.d/*.

The first custom script (*S60-ftpd*) starts the BusyBox built-in FTP server with access to the */root/app/* directory. *S60-vsftpd* is an empty file which overlays the original file so the *vsftpd* FTP server is *not* started (we need only one server). *S92-usb* script configures GPIO outputs controlling power supply to the *BudkaLighting* board (leaving the power off) and starts *udevadm* service needed to properly detect attached USB cameras when the power is turned on. *S94-ueyerec* is an empty file to *disable* direct start of the *ueyerec* application. And finally *S99-birdhouse* starts the *Birdhouse* application.

The start involves execution of several commands. First it loads the *kmod-mcc* kernel module, needed for the multi-core communication with MQX through the MCC library. Next it starts the *appmgr*^{L} process (which further starts the remaining Linux programs) and finally it starts the MQX side of the application by the following command:

```
mqxboot birdhouse_sqm4vf6_eb_m4.bin 0x3f000000 0x3f000401
```

mqxboot is a utility which loads an MQX binary file (*birdhouse_sqm4vf6_eb_m4.bin*) on a specified memory address (`0x3f000000`), starts the M4 core by enabling its clock and instructs it to execute the program from its start address (`0x3f000401`). The binary file is the MQX application built by the IAR toolchain, the addresses come from the linker configuration.

After all these steps performed, both cores are running their applications, which initialize all needed peripherals, establish inter-core communication and start doing their job as designed in Section 4.2.3.

Recording

When the application is in the *READY* mode and the infrared light barrier is disrupted, the recording operation is triggered immediately. Just to recall, the recording trigger is a long sequence of communication operations, as illustrated in Figure 38. The light barrier disruption changes the *IRDETECT* GPIO input (see schematics in Appendix B.3), which triggers a hardware interrupt handled by the *irBarrier* task. This task sets an *event* to the *appmgr*^{M} task, which sends an *MCC message* to the *appmgr*^{L} process, and that sends two *IPC messages* to the *ueyerec*^{D} process. Its IPC interface translates the message into an *internal message* type sent to the main message queue

[2]`dd` utility was used for this purpose. More in *README.txt* and *install.sh* in *sdcard/* directory on the DVD, see Appendix A.

(running in a different thread), from where the camera recording process is finally started. See Section 4.2.3 for detailed communication description.

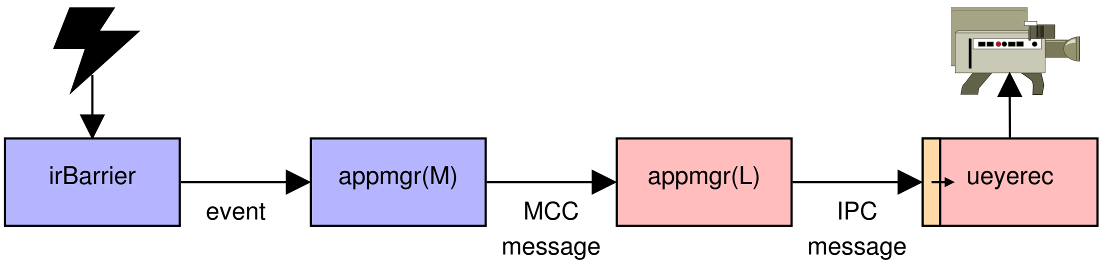


Figure 38. Recording trigger communication illustration.

Even though the uEye library contains a set of functions for outputting AVI video files, it is not available for Linux. For this reason, each frame has to be processed manually. When the camera emits the *FRAME* event, signalling a new image frame is ready in the buffer, *ueyerec* saves it as an image file.

The images stored to the buffer by the uEye API are in standard 8-bit grayscale format and 1280×1024 px dimensions, taking 1,310,720 Bytes of memory. The simplest and fastest method to store that as a standard image file is to use the Portable GrayMap (PGM) format [42] in its binary form. It just adds a very simple header before the binary data, as shows the listing below.

```
P5
1280 1024
255
<binary data ...>
```

On the first line, the format identification number is printed. There are six encoding options available ($\{BitMap, GrayMap, PixMap\} \times \{ascii, binary\}$), *P5* representing the binary GrayMap encoding. The second line states the image dimensions and the third line states the colour space scale (*0* being always black and the given maximum value – here *255* – always white).

PGM format has advantage of an easy implementation and a fast export. On the other hand, the output is too large (1,310,737 Bytes $\doteq$ 1.25 Megabytes including the header) so only a limited number of frames can be stored in the file system. That would not be a critical problem, as the individual frames are deleted after being converted to a video file. Practical problem arises here though – a limited speed of writing to the MicroSD card, where the file system is located, in conjunction with data buffering[3]. That causes the frames being saved in ‘clusters’, i.e. few subsequent frames are captured and saved correctly, then *ueyerec* operation is blocked until the file system is ready for new writes, and the process is repeated. This is undesirable behaviour of course so another way of data exporting had to be found.

Joint Photographic Experts Group (JPEG) format conversion seemed to be promising. It is an image format designed for realistic photographs, using a lossy compression based on the discrete cosine transform (DCT). That allows to reduce image size significantly, depending on the quality setting and the image content (more at [43]). In case of our video frames and 95% quality, each image takes approx. 150 kilobytes of space.

[3]Since the memory sectors in MicroSD medium can handle only a limited number of writes ($10k \sim 100k$), the driver stores the data in memory buffer until full, then it starts writing them to the medium, blocking the file write operations for some time.

Being almost ten-times smaller, all frames of one record might fit in the file system write buffer, effectively avoiding the problems with PGM export. Another problem arises here, though. JPEG compression is a complex and computationally expensive (i.e. slow) algorithm, so the maximum frame-rate is limited by this operation instead. Standard *libjpeg* library is able to produce only about 1 frame per second on our platform. An alternative library *libjpeg-turbo* was found, allowing to save from 5 to 6 frames per second, without apparent regressions on output quality and size (comparisons with *libjpeg* in [44]). That is sufficient for the *floor* camera, but not enough for frame-rate requested from the *door* camera.

To sum it up, PGM export is fast as long as the output files fit in the file system write buffer, but they do not fit there all. On the other hand, all frames encoded as JPEG might fit in the buffer (after some size optimizations), but the export is too slow by design.

A compromise solution was taken. Instead of writing the output files directly to the SD card file system, the big enough write buffer was emulated by creating a *ramdisk* in Linux file system. That is done by adding the following line to */etc/fstab* (see Appendix A):

```
tmpfs /mnt/tmp tmpfs defaults,size=90m 0 0
```

It specifies to create a disk of type *tmpfs*, i.e. a temporary file system stored in a volatile memory (RAM) and mount it under */mnt/tmp*. Its size is set to 90 MB, which is enough for storing up-to 71 PGM image frames and yet leave enough free RAM for the operating system and other running processes.

The default capture configuration – 3 seconds × 10 fps (*door* camera) + 60 seconds × 1 fps – generates 90 frames of one record, which is still more then 71. The final step of this workaround is to use both image formats – PGM for the *door* camera (short records, high frame-rate) and JPEG for the *floor* camera (long records, low frame-rate). Following this schema, one record with default configuration takes approximately $30 \times 1.31 + 60 \times 0.15 = 48.3$ MB. The reserve space provides enough freedom for performing future configuration changes.

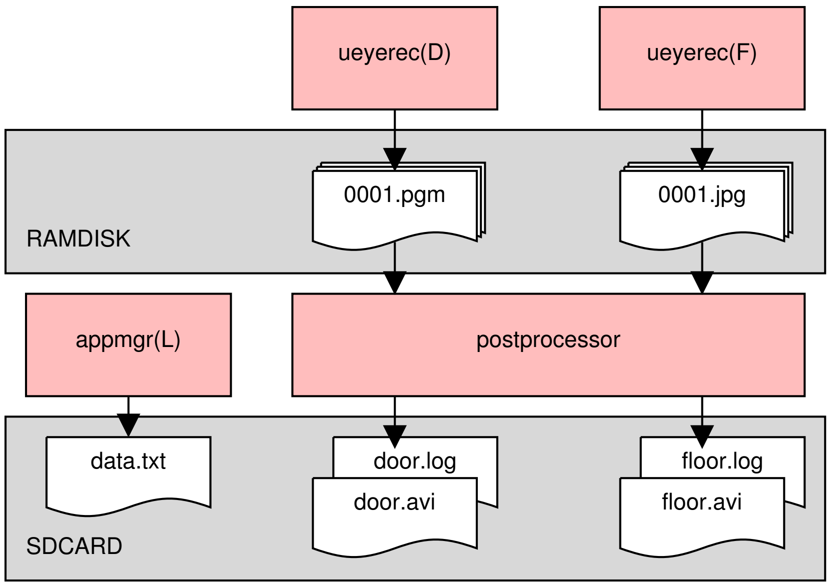


Figure 39. Illustration of flow of the recorded data.

The output image files serve as input for the *postprocessor*, whose task is to convert a sequence of images into a video file. It is the bash script *video_encode_tmp.sh* located in the */root/* directory (*<DVD>/sdcard/rfs_overlay/root/*, see Appendix A). It is run by the *appmgr*^{L} separately for each camera at the time when the camera stops recording. The script basically runs *ffmpeg* tool, which does all the video encoding job and produces an AVI file (*door.avi* or *floor.avi* for the *door* camera or *floor* camera respectively) and a log file. *appmgr*^{L} creates file *data.txt*, containing the date and time of the record, scanned RFID code (or *NONE* if no code scanned), internal and external temperature and ambient light (value from 0 to 4095, 0 being absolute dark, 4095 absolute light) – all the values received from *appmgr*^{M}. The example content of the *data.txt* file shows the following listing.

```
Date: Mon Apr 14 21:21:02 2014
RFID: 3774526282
Temperature internal: 22.75 °C
Temperature external: 0.75 °C
Ambient light: 4
```

All these five files (*door.avi*, *door.log*, *floor.avi*, *floor.log*, *data.txt*) are stored to the SD card file system together in one directory named after a timestamp of the recording start, e.g. *20140414_204103_767/* for April 14, 2014, 8:41 pm, which is placed in */root/app/data/* directory (accessible as */data/* using FTP). The recorded data flow is illustrated in Figure 39.

5.2.3. Usage

The last section of this chapter describes the application from the user's point of view and can be viewed as a simple user manual or guideline.

Application Data

This application is an autonomous system with no remote access control mechanisms. The system starts automatically when a power supply is attached, and stops normally only when the power supply is too low or detached. When the system boots, it loads its configuration files and starts its automatic operation. It collects video and textual data and stores them to a file system.

The data is accessible via the FTP service. Through FTP, the user has access only to the public part of the file system where the data is stored. An example of the public directory tree is listed in Figure 40.

The *config/* directory contains application configuration files. These will be discussed later.

The *data/* directory contains video data recorded by the application – one directory for each record. The directory is named by timestamp of the record, i.e. date and time when it was captured. Each directory contains two video files with accompanying log files and one text file with the environment state at the time of recording. For more information about the files, see Section 5.2.2.

The *log/* directory contains application log files from both MQX and Linux side of the system. They are unimportant for the user but may contain valuable data for troubleshooting in the case of application failures.

And finally the *sensors/* directory contains a list of files – each created at a new system startup – containing periodic sensors readout data. The symbolic format of their

```
/
├── config/
│   ├── linux.cfg
│   ├── log.cfg
│   └── mqx.cfg
├── data/
│   ├── 20140414_204103_767/
│   │   ├── data.txt
│   │   ├── door.avi
│   │   ├── door.log
│   │   ├── floor.avi
│   │   └── floor.log
│   ├── 20140414_212102_468/
│   │   └── ...
│   └── ...
├── log/
│   └── ...
└── sensors/
    ├── 20140414_141357.txt
    └── ...
```

Figure 40. Example of the public data directory tree.

lines is following: $\langle d\rangle\langle t\rangle : \langle t_{ONB}\rangle\ °C, \langle t_{INT}\rangle\ °C, \langle t_{EXT}\rangle\ °C, \langle l\rangle, \langle v\rangle\ V$, with the following meaning of the symbols:

$\langle d\rangle$	Date of the readout.
$\langle t\rangle$	Time of the readout.
$\langle t_{ONB}\rangle$	On-board temperature (irrelevant for the user).
$\langle t_{INT}\rangle$	Temperature inside the nest-box.
$\langle t_{EXT}\rangle$	Temperature outside the nest-box.
$\langle l\rangle$	Ambient light outside the nest-box.
$\langle v\rangle$	Measured power source voltage (not very accurate).

An example data might look as listed below. The example presents records from five following readouts, collected on April 15, 2014 after 8 pm. Since it is just about sunset, it registers the fall of the exterior light and both interior and exterior temperatures. Slight descent of the source power voltage is also noticeable (even though the absolute value is inexact).

```
2014-04-15 20:03:00: 14.50 °C, 22.50 °C, 0.50 °C, 3487, 12.256 V
2014-04-15 20:03:30: 14.50 °C, 22.25 °C, 0.25 °C, 3463, 12.255 V
2014-04-15 20:04:00: 14.50 °C, 22.00 °C, 0.25 °C, 3442, 12.253 V
2014-04-15 20:04:30: 14.50 °C, 22.00 °C, 0.25 °C, 3409, 12.253 V
2014-04-15 20:05:00: 14.50 °C, 22.00 °C, 0.25 °C, 3433, 12.254 V
```

When collecting the data, the user typically needs to download all content of *data/* and *sensors/* directories. The content of *log/* directory should also be regularly checked for system failures. If the system is in use for a higher number of cycles, the content of all these directories should be regularly cleared to ensure enough free disk space for further operation. When performing cleanup, *it is important to preserve the original directory tree*, that is the four top-most directories, *and the configuration files.*

Typical maintenance procedure might consist of the following steps:

1. Attach Ethernet cable;
2. Establish FTP connection;
3. Copy directories *data/*, *log/* and *sensors/*;
4. Check if the downloaded data is complete;
5. Delete the *content* of directories *data/*, *log/* and *sensors/*;
6. Abolish FTP connection;
7. Replace the battery;
8. Establish FTP connection;
9. Check the system is on (new file created in *sensors/* directory);
10. Abolish FTP connection;
11. Detach Ethernet cable.

Application Configuration

The application is parametrized by two user configuration files – *linux.cfg* and *mqx.cfg* – stored in the */config/* directory (accessible using FTP). *mqx.cfg* configures the MQX side of the application, i.e. the main application control, while *linux.cfg* configures the Linux side, which reduces only to the main cameras configuration settings. Both files have different syntax and are described below.

The default content of the *mqx.cfg* file is as follows:

```
#lwcfg config file
sleep_enable=1
sleep_hour=7
sleep_minute=00
wakeup_hour=19
wakeup_minute=00
battery_low=12000
battery_verylow=11850
battery_critical=11750
```

The first line is a comment and can be ignored. Each of the remaining lines contains one record of the form ⟨*key*⟩ = ⟨*value*⟩. User can modify the values according to the description in Table 4. Please note that *battery_verylow* and *battery_critical* should better be set to lower values as the battery voltage measurement does not perform accurately. Also note that *halting* the system is a controlled operation (with all files being saved properly) while *turning off* the system is a hard system power down.

Key	Allowed Values	Description
sleep_enable	0 or 1	Use 1 to enable the power-saving *SLEEP* mode, when the video recording is disabled. Use 0 to disable it.
sleep_hour sleep_minute	0 to 23 0 to 59	Hour and minute of the day when to switch to *SLEEP* mode. *sleep_enable* must be 1 to take effect.
wakeup_hour wakeup_minute	0 to 23 0 to 59	Hour and minute of the day when to switch to *READY* mode. *sleep_enable* must be 1 to take effect.
battery_low	1 to 13000	Battery voltage (in millivolts) when to *warn* about low voltage.
battery_verylow	1 to 13000	Battery voltage (in millivolts) when to *halt* the system.
battery_critical	1 to 13000	Battery voltage (in millivolts) when to *turn off* the system.

Table 4. *mqx.cfg* configuration keys description.

The default content of the *linux.cfg* file is as follows:

```
# Door camera settings
dcam:
{
  # sensor gain <0,100> - increment to increase sensitivity
  gain = 10;
  # camera exposure <0.5,50.0> ms - increment to increase lightness
  exposure = 6.0;
  # number of frames per second <0.1,10.0> fps
  framerate = 10.0;
  # video record duration <0.1,300.0> s
  duration = 3.0;
};

# Floor camera settings
fcam:
{
  # sensor gain <0,100> - increment to increase sensitivity
  gain = 10;
  # camera exposure <0.5,50.0> ms - increment to increase lightness
  exposure = 6.0;
  # number of frames per second <0.1,10.0> fps
  framerate = 1.0;
  # video record duration <0.1,300.0> s
  # The sum of both durations must be smaller then 300 s!
  duration = 60.0;
};
```

The file contains two groups – *dcam* for the *door* camera configuration, and *fcam* for the *floor* camera configuration. Both groups contain the same configuration records of the form $\langle key \rangle = \langle value \rangle$; with each being commented (preceding line(s) beginning with the # character). Please, note that it is preferable to increase *gain* rather than *exposure* to accomplish brighter records, as the longer exposure time decreases the maximum frame-rate. Remember that the sum of *durations* of both cameras has to be smaller then 300, and that the temporary output buffer has a limited capacity so the weighted sum of products of $\langle framerate \rangle \times \langle duration \rangle$ must not be too high (see Section 5.2.2 for explanation and computation of maximum allowable values).

When the configuration is being changed, the system must be reset afterwards, as‘the configuration files are read only during system startup (described in Section 5.2.2). It is also recommended to wait for five minutes before the system is reset so all the changes are flushed from the file system buffer to the hardware medium.

System Configuration

Much more powerful configuration and administration options are available through a direct access to the Linux operating system. That includes, for example, the date and time configuration, network configuration or password changes, but also updates of the application binaries and complete system control. All these possibilities are available when accessing the system through *ssh* or *telnet* services, being logged in as the *root* user. That should be done by *experienced users* only though! Standard use of the system should not require that level of administration.

6. Experiments

When the system was finally successfully completed, multiple experiments were performed to verify its proper functioning. This chapter describes those most important.

6.1. Indoor Testing

Two main experiments were performed indoor, validating the system is ready for autonomous use outdoor.

6.1.1. Power Consumption

First, it was needed to check if the system is able to run autonomously for seven days without the need to change the battery. Because the ornithologists wanted to use it for their outdoor research in Spring 2014 breeding season, there was not enough time to do a week-long test with the battery. For this reason it was decided to measure instantaneous power consumption by ammeter and *compute* theoretical length of the system run without the need to replace the battery.

The system was powered from hard 12 V power source. It ran continuously from one day afternoon to second day morning, so both *SLEEP* and *READY* modes were run for long enough time. In the *READY* mode, the light barrier was disrupted multiple times, so the *RECORDING* mode was tested, too. In all modes, several measurements of instantaneous power consumption were noted. Their averaged values are listed in the second column (*Current*), Table 5.

Mode	Current	Power	Holding Time
SLEEP	169 mA	2.03 W	14.77 days
READY	308 mA	3.70 W	8.11 days
RECORDING	351 mA	4.21 W	7.12 days

Table 5. Averaged measurements of instantaneous system power consumptions.

From the knowledge of the power source voltage, the system power was computed ($I \cdot U = \langle current \rangle \cdot 12$), as listed in the third table column (*Power*). The theoretical battery capacity is $12\ V \cdot 60\ Ah = 720\ Wh$, from where the length of continuous run in given mode was computed (*Holding Time*).

The table shows that the system should theoretically be able to run for seven days even in the *RECORDING* mode. Here it is important to admit that accuracy of this mode consumption measurements was not probably very good, as the flashing IR lighting causes short but high consumption peaks which are not possible to be measured by a simple ammeter.

Anyway, taking into account the results of the *SLEEP* mode and *READY* mode theoretical holding times, their combination (according to the default configuration) gives about 11 days holding time. A few tens of minutes of the *RECORDING* mode being active each night should not change the results too much. In any case, the reserve should be big enough to guarantee a week-long run of the system without damaging the battery. More exact power consumption testing can hardly be performed without undergoing the real 7-day test.

6.1.2. Prey Simulation

The second experiment was to simulate the bird fly-in with prey delivery and collect recorded data as it was in real operation. Since the experiment was taken at daytime, switch to the *READY* mode was enforced manually using the testing on-board buttons (see Section 5.1.1). Instead of the prey, living hamster was used, being simply thrown into the nest-box by hand. Please note this experiment did *not* cause the hamster any harm.

When the hamster first disrupted the light barrier, *door* camera started recording of 3 seconds long sequence with 10 fps frame-rate. The first frames captured the hamster falling inside the nest-box, as shown in Figure 41. The remaining frames did not carry any useful information. Immediately after the *door* recording stopped, the *floor* camera started recording its 60 seconds long sequence with 1 fps frame-rate. The hamster moving on the box ground was recorded, 3 subsequent frames are for illustration depicted in Figure 42.

Content of accompanying *data.txt* file is listed below:

```
Date: Mon Apr  7 13:24:26 2014
RFID: NONE
Temperature internal: 19.50 °C
Temperature external: 18.75 °C
Ambient light: 1281
```

Complete data, including the sensor readouts and application logs can be found on the accompanying DVD in the *experiments/indoor/* directory (see Appendix A). It shows that the application operated correctly and recorded all data as expected.

6.2. Outdoor Testing

Neither tens of hours of indoor testing undertaken, nor the indoor experiments described in Section 6.1 can guarantee the full system functionality in the final application with no supervision. Besides there was no time to do some longer supervised experiments in the outdoor environment, as there was a pressure to already install the system in the field. It was decided to skip further testing efforts for these reasons and undergo 'baptism by fire'.

Since the system never ran for longer then 24 hours, the most probable risks of this approach were:

- The system might crash after some time without recovering, hence loosing potentially unrecorded data.
- The system might completely drain the battery, which might get damaged.

Obviously, the first point would come true for sure if the decision was to do more supervised experiments, so the only main risk of the decision was potential battery damage. The ornithologists valued their research more than one battery, so the described decision was taken. It was decided to do first battery replacement after a 4-day run only to at least eliminate the battery damage risk.

The system configuration was changed slightly. The *floor* camera was set to record only 30 seconds long sequences but with 4 fps frame-rate. The rest of cameras config-

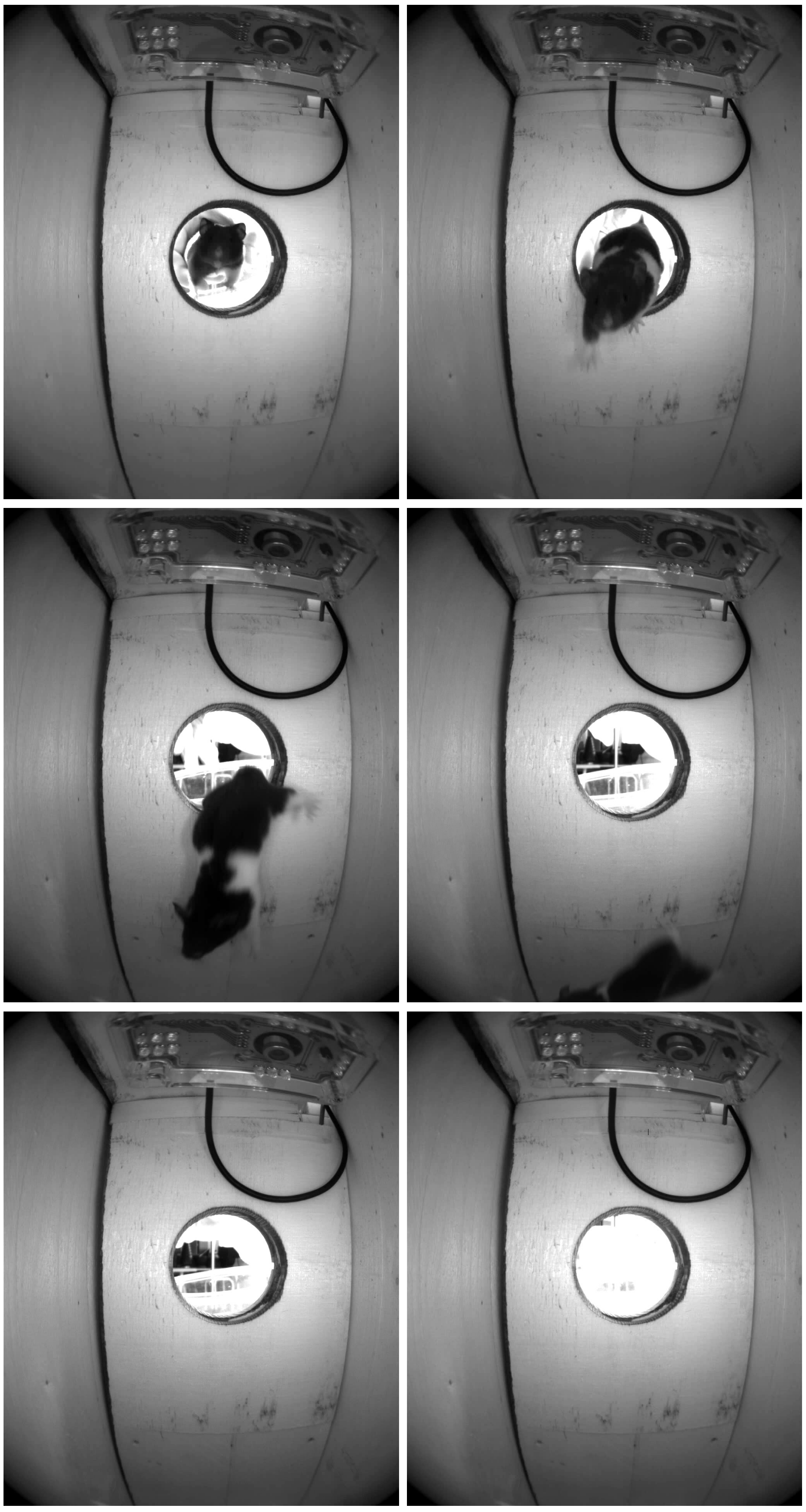


Figure 41. First 6 frames captured by the *door* camera in the *prey simulation* experiment.

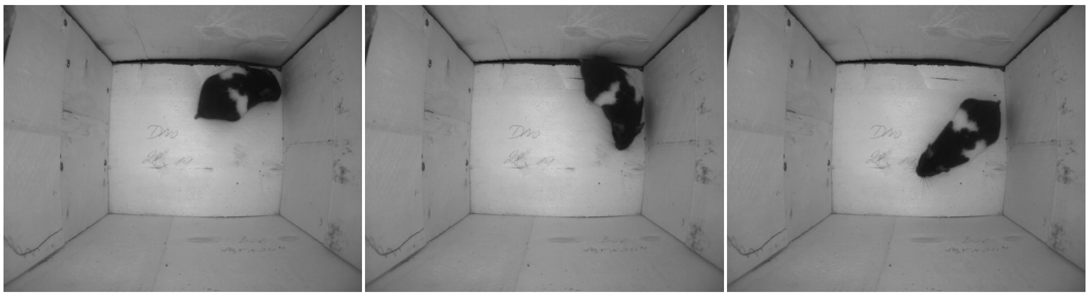


Figure 42. Three of frames captured by the *floor* camera in the *prey simulation* experiment.

uration was left unchanged. The *wakeup time* was changed to 8 pm and the battery voltage thresholds were set to highly improbable values so the system does not turn off due to the voltage checks (the *low* threshold was set to 12,000 mV, *verylow* to 11,000 mV and *critical* to 10,000 mV).

The system was installed on Monday, April 14, 2014, in Ore mountains, Czech Republic (Figure 43). The ornithologists replaced a plain nest-box occupied by nesting Tengmalm's owls by this system, moving the nest including eggs to the new nest-box, and tagged the parents by PIT tags. They powered on the system and left the place. After 4 days, on Friday, April 18, 2014, they returned and collected the data following the guideline from Section 5.2.3, without experiencing any problems. In the end, they replaced the battery, and after evaluation that no serious problem occurred, they left the place, leaving the system running for the new cycle.

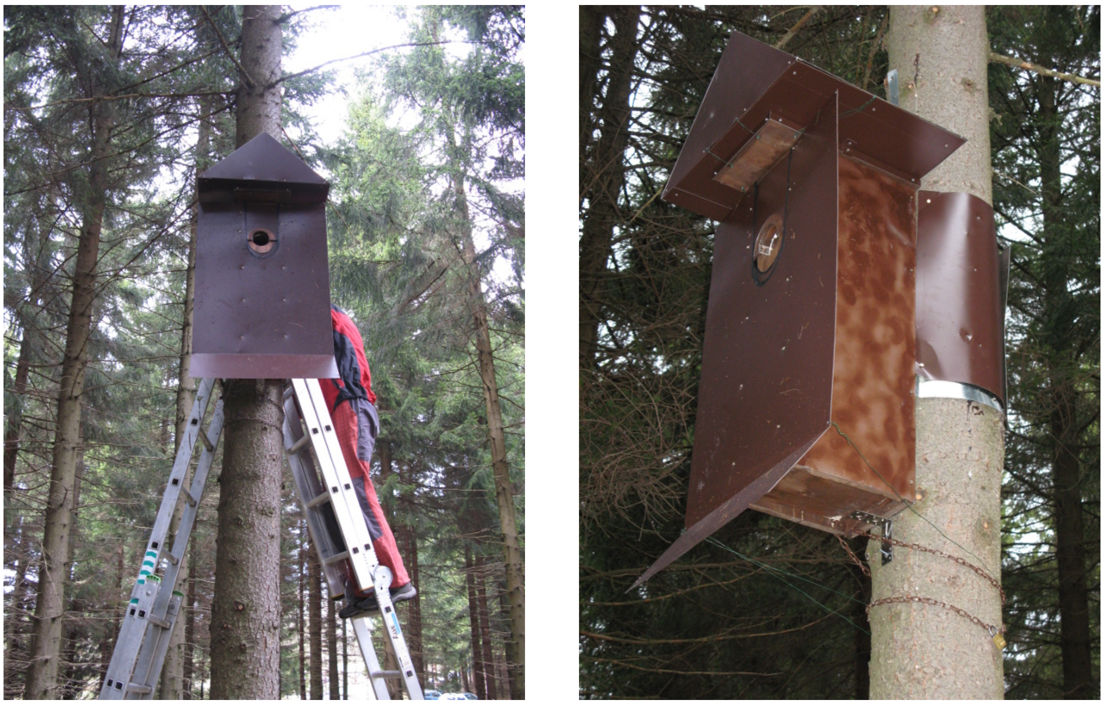


Figure 43. Installation of the nest-box by ornithologists in the field. The box is covered by additional plating. (Photos by the ornithologists.)

Collected data was provided by the ornithologists for detailed analysis, it can be found on the DVD in the *experiments/outdoor* directory (see Appendix A). On the first sight the system worked very well. According to the logs and number of files in the */sensors/*

directory, the system started three times. The first two starts happened in the morning (9:51 and 10:04) of Monday 14th and the runs were very short, apparently being just kinds of testing or configuration runs. The last time the system started at 14:13, and it ran continuously until Friday 18th, 8:22, when the battery was detached.

During the four nights, 48 records were collected. Almost half of the records (22) was captured during the first night because the female left and returned many times – maybe the birds were nervous about the new nest-box, but it is not the deal of this document to discuss the birds' behaviour. There are from 6 to 11 records at the other nights. Some of the records capture the female first leaving the nest, and then returning back after few minutes. The remaining records capture prey delivery by the male and its handover to the female.

Lets discuss deeply the Wednesday evening (April 16, 2014). The first record of that night (*20140416_212355_941*) was captured at 21:23:55 when the female left the box. Fly-out typically takes from 15 to 30 seconds, so there is only feather visible on the *door* record (see the left picture in Figure 44). First half of the *floor* camera record contains only feather, too, then the female leaves and empty nest is visible, containing 4 eggs (right picture in Figure 44).

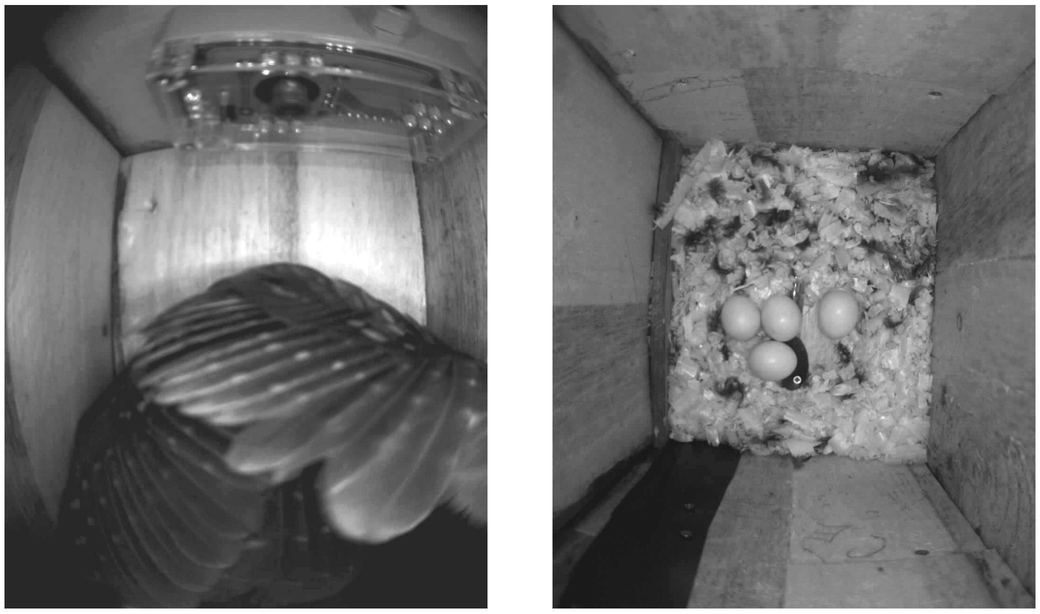


Figure 44. Record of the female leaving the nest-box. The left frame comes from the *door* camera, the right frame from the *floor* camera. (Data by the ornithologists.)

In comparison with indoor testing, the records are pretty dark. It is caused first by no ambient exterior light, and second by much darker scene (the real nest-box sides are darker in comparison with the testing box, and the owl is also dark). That can be easily fixed by incrementing cameras gain or exposure in the configuration files.

The files *door.log* and *floor.log* reveal records frame-rates. The *door* record was recorded with 10 fps, as expected, while the *floor* record had lower frame-rate then configured – only 2.57 fps instead of 4 fps. This is not caused by the speed of JPEG export, but by simultaneous processing of the *door* record by *ffmpeg* and recording of the *floor* record by *ueyerec*^{F}. Since Linux is not a real-time operating system, it is complicated to ensure the requested frame-rate. Even though it provides a priority mechanism (which was used), the priorities are not absolute – processes with higher priorities are just given more processor time then others, but the other processes also get some, leading to the observed behaviour. It is not an ideal situation, but on the other hand the problem is not critical, at least not for this application.

From the file *data.txt* listed below we can see the internal temperature was 25.75 °C (the sensor was placed amongst the eggs) while outside it was 0 °C and complete dark. The RFID tag was scanned properly.

```
Date: Wed Apr 16 21:23:55 2014
RFID: 3774526282
Temperature internal: 25.75 °C
Temperature external: 0.00 °C
Ambient light: 3
```

The female returned 5 minutes later, at 21:28:40 (record *20140416_212840_033*). The *door* camera recorded the female passing through the fly-in hole (Figure 45, left image), while the *floor* camera recorded the owl landing on the box ground and sitting on the eggs (Figure 45, right image).

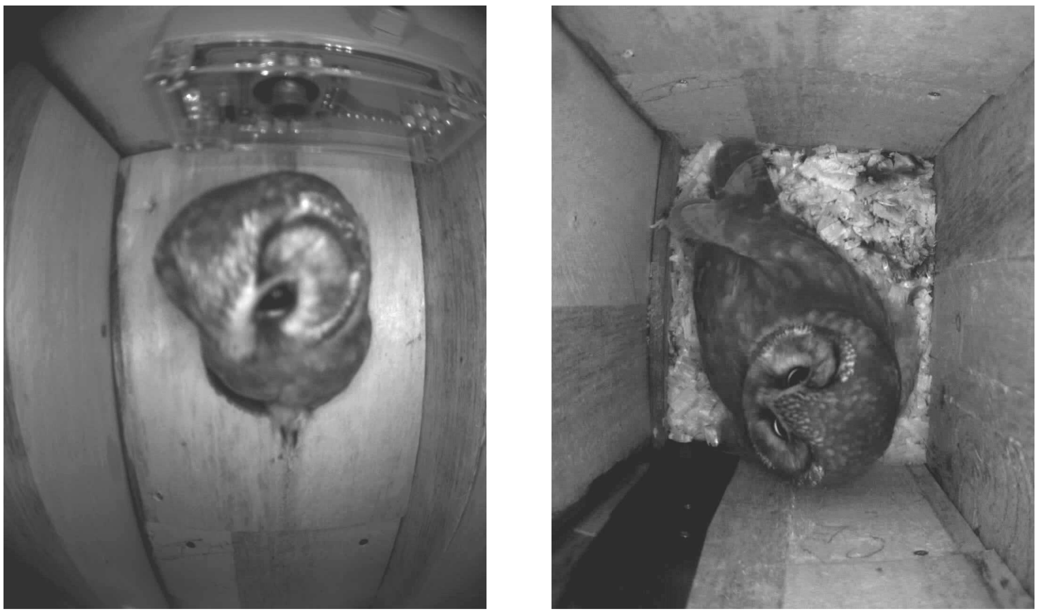


Figure 45. Record of the female returning to the nest-box. The left frame comes from the *door* camera, the right frame from the *floor* camera. (Data by the ornithologists.)

Frame-rate of the *door* record was 10 fps as expected. The *floor* record frame-rate was 3.07 fps for the same reasons that were described above.

From the *data.txt* file (below) we can see now both internal and external temperatures fell down. The internal temperature dropped by 6 degrees, while the external temperature dropped just by 0.25 °C. First software bug is discovered here, as the temperature is stored in an `unsigned char` variable, so 255.75 °C is printed instead of -0.25 °C. To get the real temperature, user needs to subtract value 256. The bug is easy to fix for the next real operation after the expected maintenance. The exterior light also dropped from 3 to 2, but it has no real meaning as the sensor is already under-exposed and these fluctuations are generally caused by noise. The same RFID tag was scanned again.

```
Date: Wed Apr 16 21:28:40 2014
RFID: 3774526282
Temperature internal: 19.50 °C
Temperature external: 255.75 °C
Ambient light: 2
```

The following record *20140416_212919_941* comes the very next moment, at 21:29:19, when the male brings a prey – a kind of rodent. The *door* camera recorded the male transmitting the prey to the female (Figure 46, left image) while the *floor* camera captured the female placing the food on the ground (Figure 46, right image) and further sitting on the eggs.

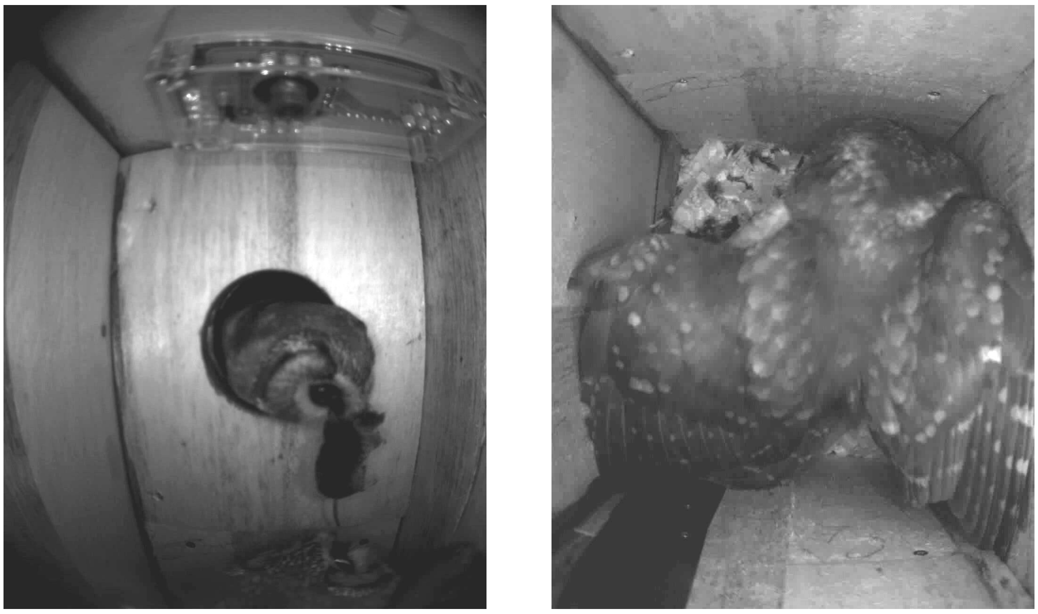


Figure 46. Record of the male bringing a prey. The left frame comes from the *door* camera, the right frame from the *floor* camera. (Data by the ornithologists.)

In this case, frame-rates of both records were lower – 4.67 fps for the *door* camera and 2.30 fps for the *floor* camera. The reason is that new recording started almost immediately after the previous one was finished – but *finished* here means the moment when the *floor* camera stopped recording, not when the frames post-processing was complete. So the cause is the same as in previous cases where it influenced only the *floor* camera. Again, it is not ideal situation, but better to have a record with lower frame-rate then to miss it completely – it still provides all needed data.

The most important information from the *data.txt* file (listed below) is the missing RFID code. This is typical result of this part of the system – while the female is usually scanned properly (as it always passes *through* the RFID antenna), the male usually fails to be scanned (as it keeps its legs *outside* of the hole). This can be considered the biggest issue found during the analysis. The RFID antenna probably needs to be adjusted to improve the result.

```
Date: Wed Apr 16 21:29:19 2014
RFID: NONE
Temperature internal: 19.25 °C
Temperature external: 255.75 °C
Ambient light: 2
```

Last thing to be evaluated is the power consumption. According to the source power voltage measurements (recorded in the *sensors/20140414_141357.txt* file), the initial voltage was about 12.75 Volts and the final voltage was only about 12.11 Volts. Similar results were reported by the ornithologists. Even though both measurements are probably pretty inexact (the ornithologists used a very cheap voltmeter), the battery was surely discharged more then expected, as according to the battery manual 12.1 V corresponds to only 25% remaining energy. On the other hand, the results are influenced by several aspects:

- The measurements were not very precise,
- the battery might not had been fully charged at the beginning,
- the nights were very cold[1], which decreases the battery performance.

To sum the results of the experiment, it verified the system to work correctly, autonomously and reliably, providing high quality data useful for further research. Besides few trivial issues (the negative temperature bug and low video brightness) and one issue of low importance (lower frame-rate than requested), the RFID reader was found not to perform reliably, and the overall power consumption was found to be perhaps higher then expected, but that needs to be further tested. In any case, the overall results are very positive.

[1]The lowest temperature measured by the exterior sensor was -4.75 °C.

7. Conclusion

This document described the development, implementation and testing of a new video surveillance system embedded in a bird nest-box. Such a system was needed by ornithologists from the Czech University of Live Sciences Prague for research of breeding and foraging strategy of Tengmalm's owl.

The work involved development of both hardware and software equipment of the system. It started by selection of appropriate platform and building blocks. The system was built on the SQM4-VF6-W processor module with the new heterogeneous dual-core microprocessor Freescale Vybrid VF6. The custom control board and several peripheral boards were developed and manufactured by Elnico s.r.o., which also provided for free the development tools and libraries and exhaustive support. Infra-red light sensitive monochromatic HD cameras UI-1541LE by IDS Imaging Development System GmbH were used for video capturing.

The system software was based on two operating systems – Linux OS® on the first core and Freescale MQX™ RTOS on the second core. Development of the application software involved design and implementation of a Linux video recording application and a control interlink application, and an MQX application controlling the system logic and peripherals.

The system has been already delivered to the ornithologists and tested in practice. It showed to be fully functional, producing quality video records of observed owls and multiple additional types of data. A few issues are yet to be tested and solved, for example possibly higher power consumption than expected or unimplemented Wi-Fi interface which would allow to download the data and control the system remotely without owls disturbance.

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Appendix A.
DVD Content

This thesis is accompanied by a data DVD containing the software resources used and developed in terms of this work. Its structure is listed here.

```
DVD/
├── appendices/
│   ├── pcbs/ ........................................ PCBs from appendix C
│   │   └── ...
│   ├── photos/ .................................... photos from appendix D
│   │   └── ...
│   └── schematics/ ........................... schematics from appendix B
│       └── ...
├── experiments/
│   ├── indoor/ ................................... prey simulation output
│   │   └── ...
│   └── outdoor/ ............................................ real output
│       ├── config/
│       │   ├── linux.cfg ............................ linux-side configuration
│       │   ├── log.cfg ................... log-counter internal configuration
│       │   └── mqx.cfg ............................... mqx-side configuration
│       ├── data/
│       │   ├── 20140414_204103_767/ ................. first record directory
│       │   │   ├── data.txt ................................ record summary
│       │   │   ├── door.avi ............................ fly-in camera record
│       │   │   ├── door.log ............................... fly-in camera log
│       │   │   ├── floor.avi ........................... ground camera record
│       │   │   └── floor.log .............................. ground camera log
│       │   ├── 20140414_212102_468/ ................ second record directory
│       │   │   └── ...
│       │   └── ...
│       ├── log/ ............................................ application logs
│       │   └── ...
│       └── sensors/ ............................ lists of sensors readouts
│           ├── 20140414_095131.txt
│           ├── 20140414_100441.txt
│           └── 20140414_141357.txt
├── linux_sdk/ ................................... SDK generated by Factory
│   ├── bootloader/
│   │   ├── u-boot.imx ......................................... U-Boot binary
│   │   └── ...
│   ├── kernel-source/ ..................... complete kernel source files
│   │   └── linux-3.0/
│   │       ├── .config ............................... kernel configuration file
│   │       └── ...
│   ├── rfs/
│   │   └── rootfs.tar.gz ........................... device filesystem image
│   ├── toolchain/ ............................ build tools, libraries, etc.
│   │   └── ...
│   ├── .config ................................ workorder configuration file
│   ├── uImage-3.0-ts-armv7l ............................ Linux kernel binary
│   └── ...
└── ...(see the next page)
```

```
DVD/
├── ...(continued from the previous page)
├── sdcard/
│   ├── rfs_overlay/ ................................additional RFS data
│   │   ├── etc/
│   │   │   ├── init.d/ .................................system init scripts
│   │   │   │   ├── S60-ftpd
│   │   │   │   ├── S60-vsftpd
│   │   │   │   ├── S92-usb
│   │   │   │   ├── S94-ueyerec
│   │   │   │   └── S99-birdhouse
│   │   │   └── fstab
│   │   └── root/
│   │       ├── app/ ..............................application data directory
│   │       │   ├── config/
│   │       │   │   ├── linux.cfg
│   │       │   │   └── mqx.cfg
│   │       │   ├── data/
│   │       │   ├── log/
│   │       │   └── sensors/
│   │       ├── appmgr .....................................appmgr^L binary
│   │       ├── birdhouse_sqm4vf6_eb_m4.bin ..........MQX application binary
│   │       ├── mcfsd ................................MCFS daemon binary
│   │       ├── ueyerec .....................................ueyerec binary
│   │       └── video_encode_tmp.sh ....................postprocessor script
│   ├── README.txt ........................SD card preparation comments
│   └── install.sh ...........................SD card installation script
├── src/
│   ├── appmgr/ ......................................appmgr^L source files
│   │   └── ...
│   ├── birdhouse/ ..........................MQX application source files
│   │   ├── iar/ ..........................................IAR project files
│   │   │   └── ...
│   │   ├── libesl/ ...............................ESL library distribution
│   │   │   └── ...
│   │   ├── libmqx/ ...............................MQX library distribution
│   │   │   └── ...
│   │   └── ...
│   └── ueyerec/ .....................................ueyerec source files
│       └── ...
└── thesis.pdf .......................electronic version of this document
```

Appendix B.

Schematics

Schematics of all custom boards, developed by Elnico s.r.o.

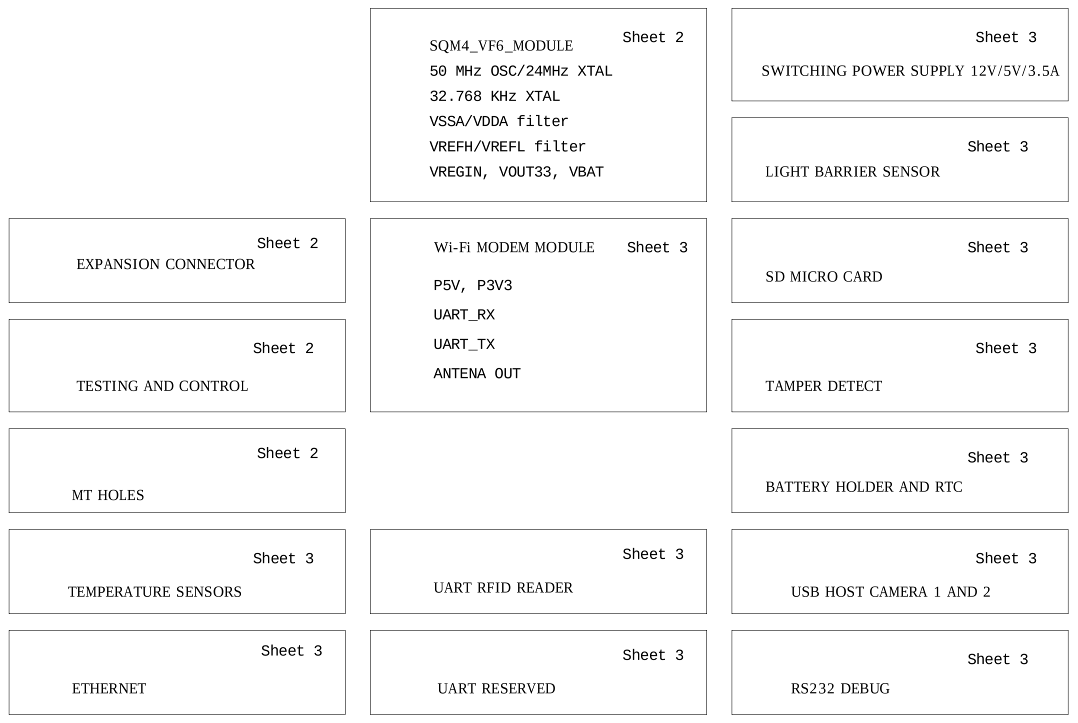
B.1. BudkaControl

Schematics of the control board named *BudkaControl*. *WIFI MODEM - MODULE* and *external RTC* are not placed.

Table of Contents	
1	Block Diagram
2	SQM4-VF6 +WiFi
3	Peripherals
4	
5	
6	
7	

Revisions

Rev	Description	Date	Approved
A	Proto Release	20 Aug 13	J.K.
B			
C			



1. Unless Otherwise Specified:
   All resistors are in ohms
   All capacitors are in uF
   All voltages are DC
   All polarized capacitors are aluminum electrolytic

2. Interrupted lines coded with the same letter or letter combinations are electrically connected.

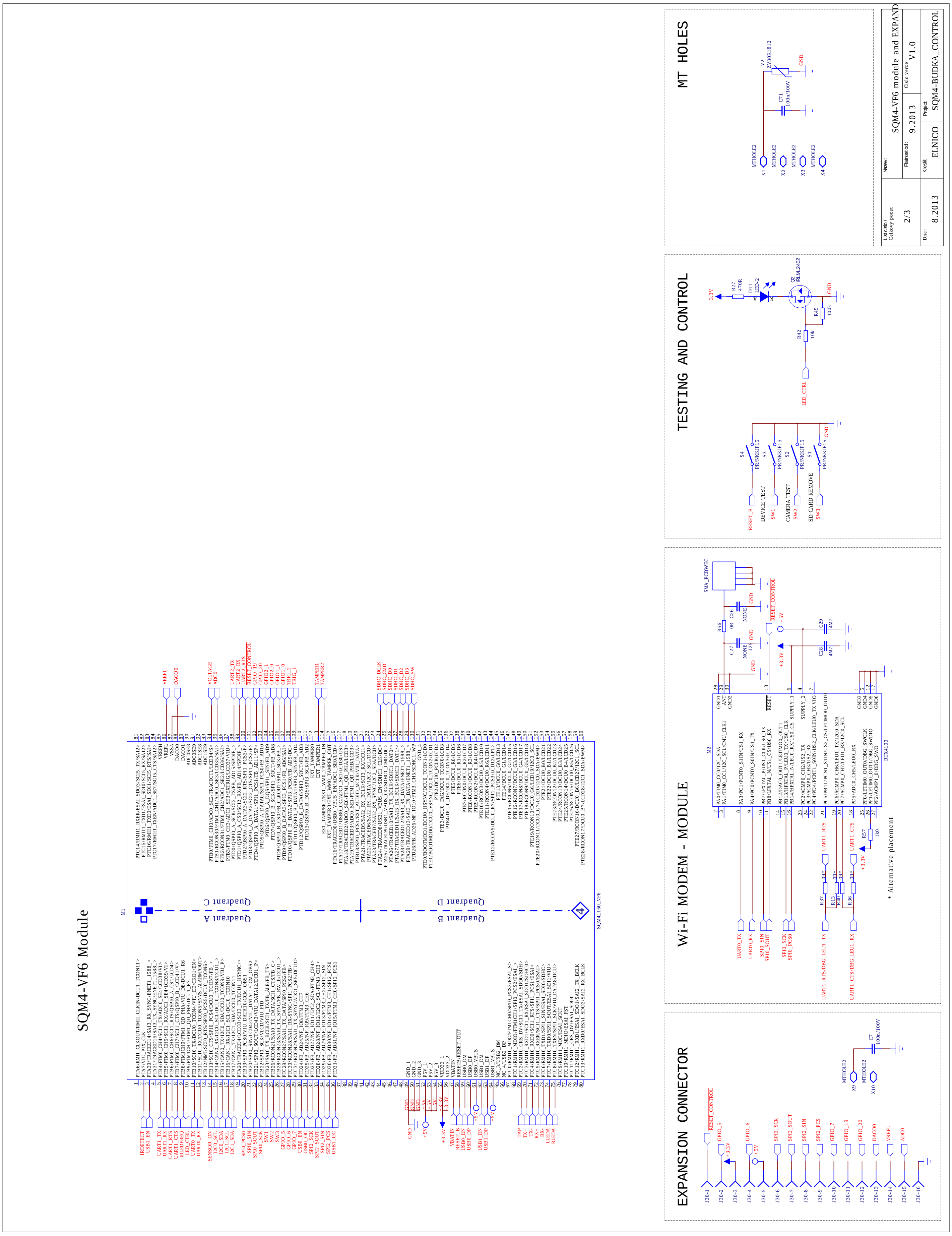
3. Device type number is for reference only. The number varies with the manufacturer.

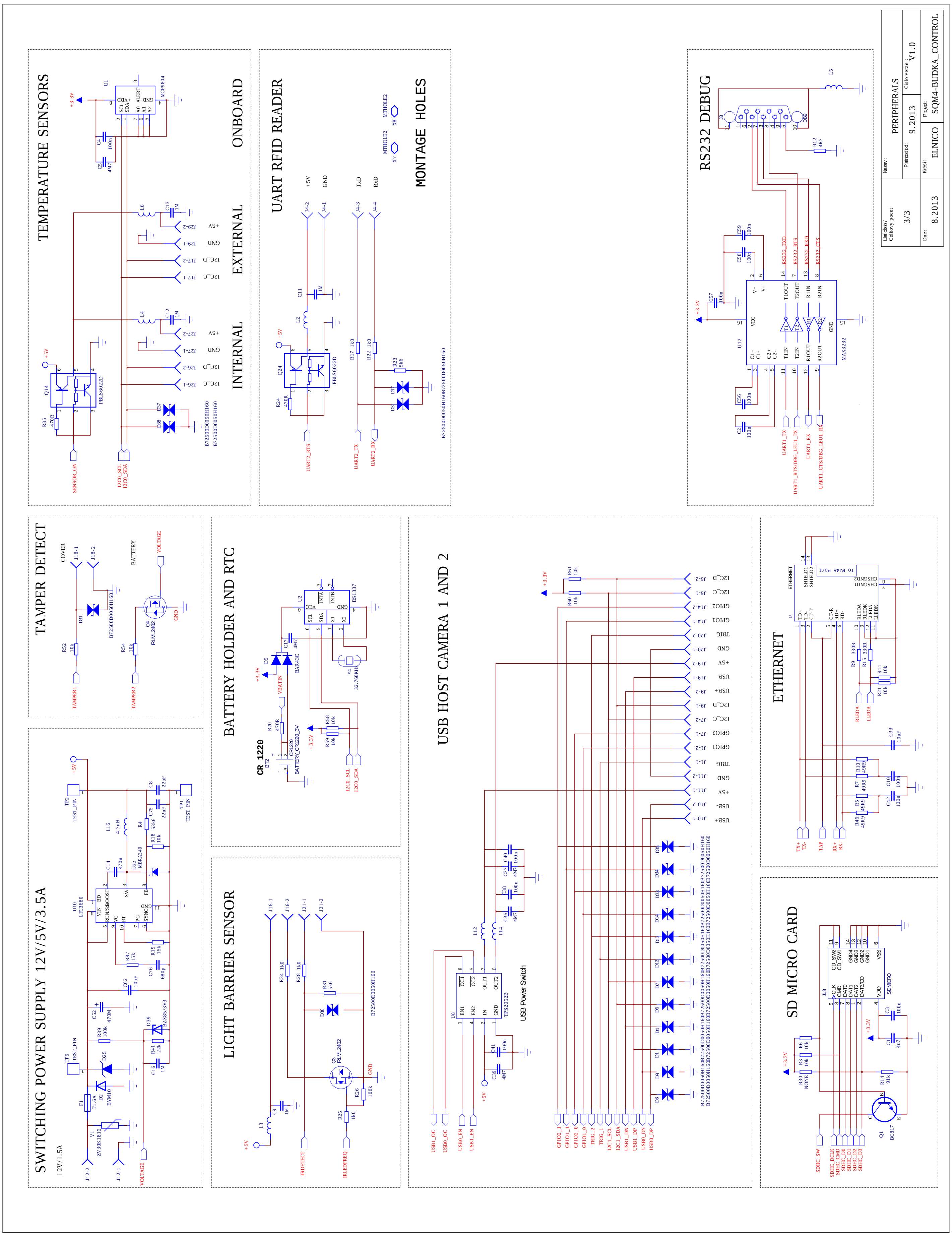
4. Special signal usage:
   _B Denotes - Active-Low Signal
   <> or [] Denotes - Vectored Signals

Power & Ground Nets

NET	VOLTAGE	DESCRIPTION
+5V	5V	Primary input power. Input to USB power switch.
+5V_USB	5V	Secondary input power. Filtered from USB connector. Input to USB power switch.
P5V_SW	5V	Output of USB power switch controlled by the 5V_EN signal from the JM60 MCU. Used by OSBDM voltage translation circuits.
P5V_TRG_USB	5V	Output of USB power switch controlled by the VTRG_EN signal from the JM60 MCU. Provides input to regulator.
+3.3V	3.3V	Output of regulator using USB power input (P5V_TRG_USB).
P3V3_MCU	3.3V	MCU digital power. Filtered from +3.3V.
VDDA	3.3V	VDDA power for MCU and analog circuits. Filtered from P3V3_MCU.
VREFH	3.3V	Upper reference voltage for ADC on the MCU. Filtered from VDDA.
VREFL	0V	Lower reference voltage for ADC on the MCU. Filtered from VSSA.
VSSA	0V	VSSA power for MCU and analog circuits. Filtered from GND.
GND	0V	Digital Ground.

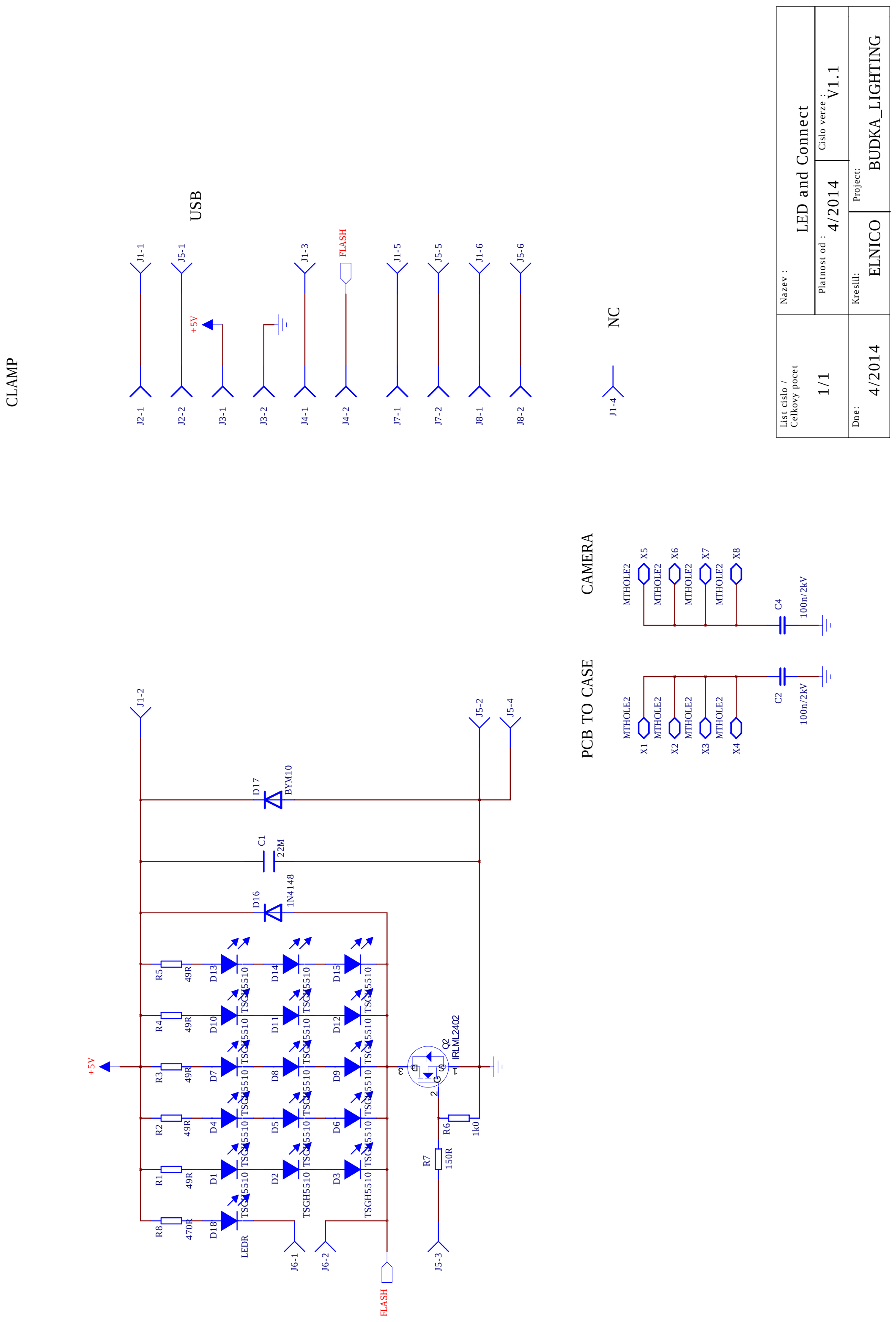
List cislo / Celkovy pocet: 1/3	Nazev: BLOCK_DIAGRAM	
	Platnost od: 9.2013	Cislo verze: V1.0
Dne: 8.2013	Kreslil: ELNICO	Project: SQM4_BUDKA_CONTROL


SQM4-VF6 Module
EXPANSION CONNECTOR
Wi-Fi MODEM - MODULE
TESTING AND CONTROL
MT HOLES
SQM4-VF6 module and EXPAND
V1.0
9.2013
ELNICO
SQM4-BUDKA_CONTROL
2/3
8.2013


TEMPERATURE SENSORS
ONBOARD
EXTERNAL
INTERNAL
UART RFID READER
MONTAGE HOLES
RS232 DEBUG
TAMPER DETECT
BATTERY HOLDER AND RTC
USB HOST CAMERA 1 AND 2
ETHERNET
SWITCHING POWER SUPPLY 12V/5V/3.5A
LIGHT BARRIER SENSOR
SD MICRO CARD
USB Power Switch
CR 1220
PERIPHERALS
V1.0
9.2013
SQM4-BUDKA_CONTROL
ELNICO
3/3
8.2013

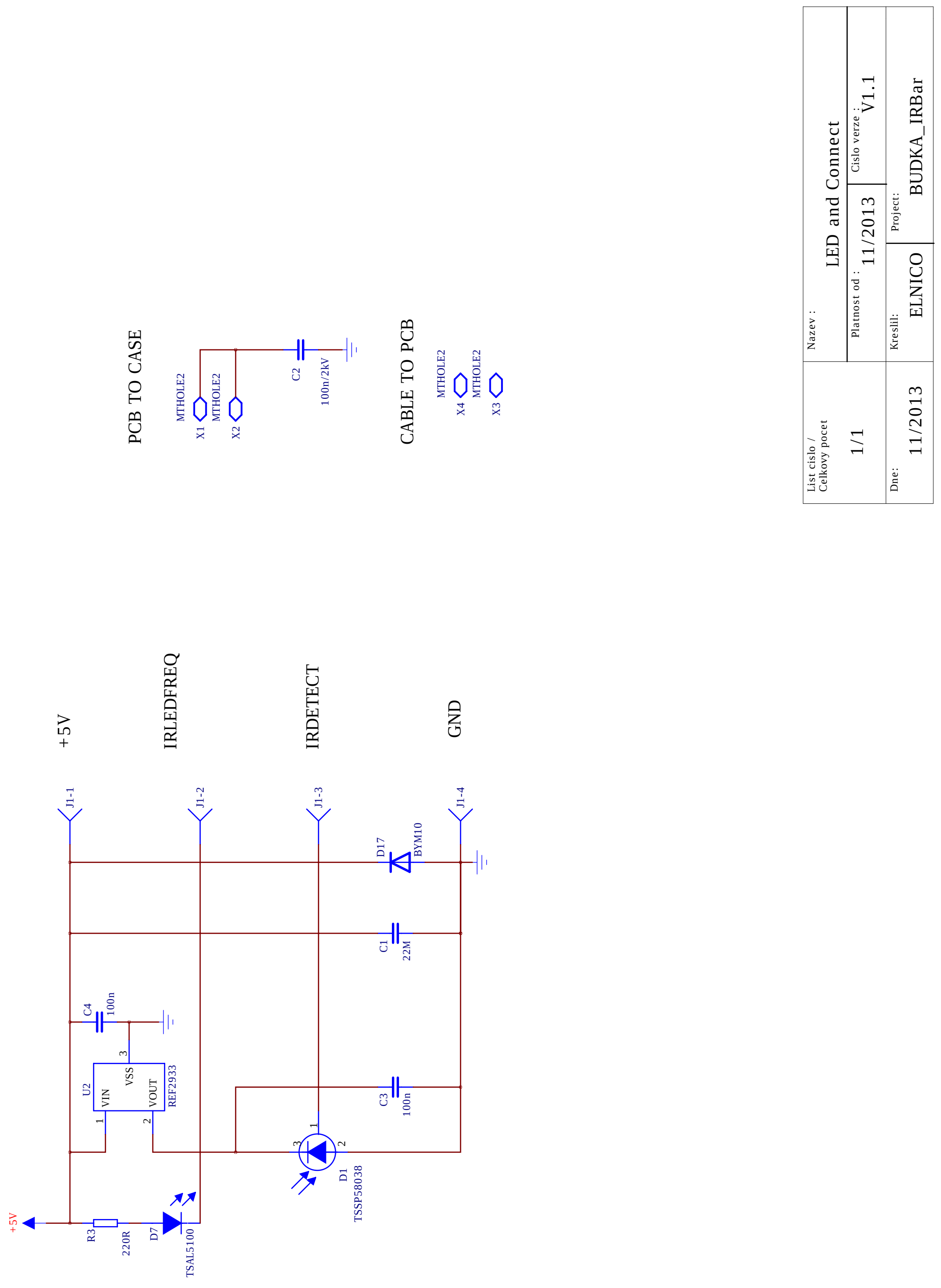
B.2. BudkaLighting

Schematics of the camera infrared lighting board named *BudkaLighting*.



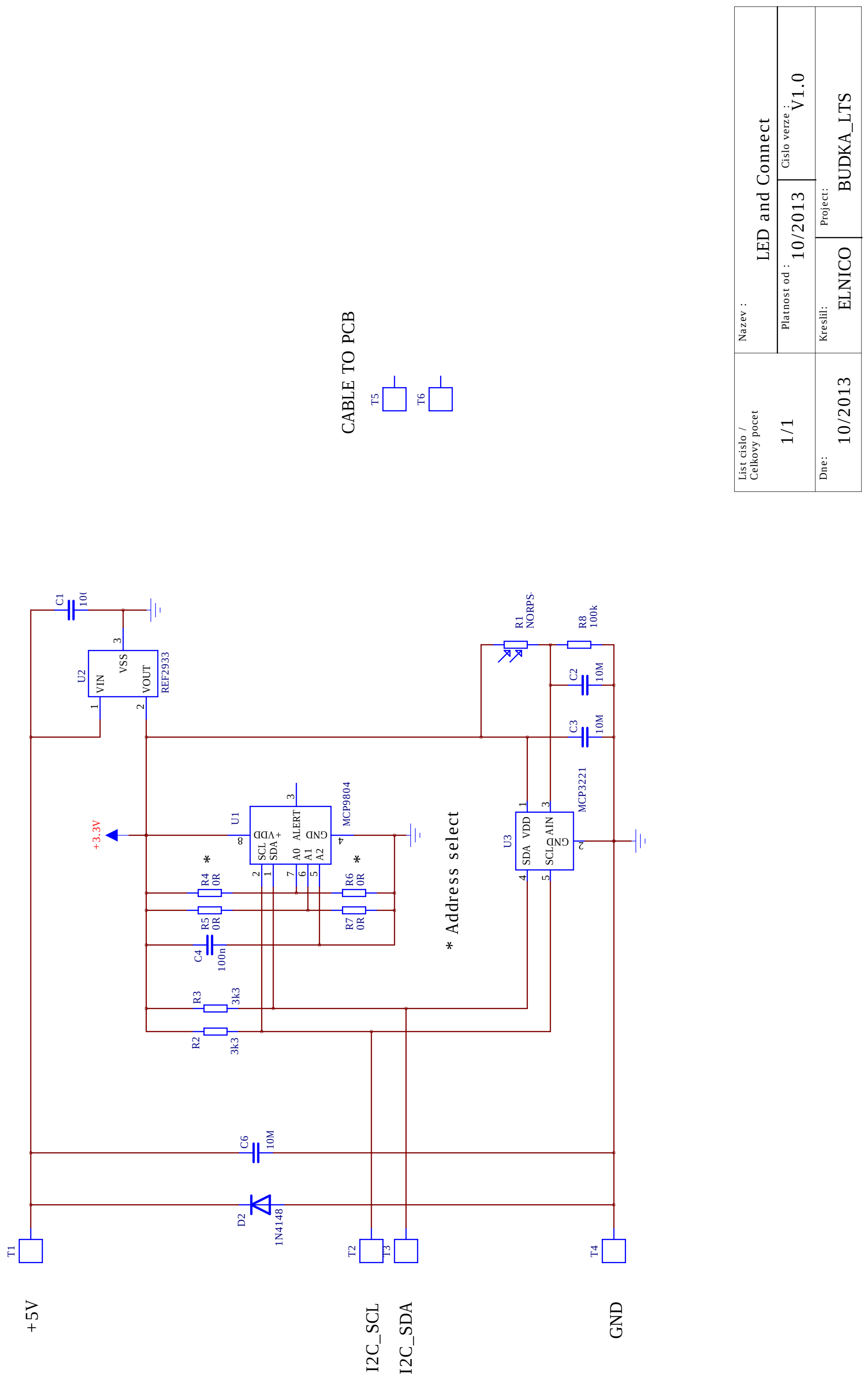
B.3. BudkaIRBar

Schematics of the infrared light barrier board named *BudkaIRBar*.



B.4. BudkaLTS

Schematics of the temperature and light sensors board named *BudkaLTS*.



Appendix C.

Printed Circuit Boards

Board routings and silkscreens of the printed circuit boards, assembled by Elnico s.r.o.

C.1. BudkaControl

Routings and silkscreens of the control board named *BudkaControl*.

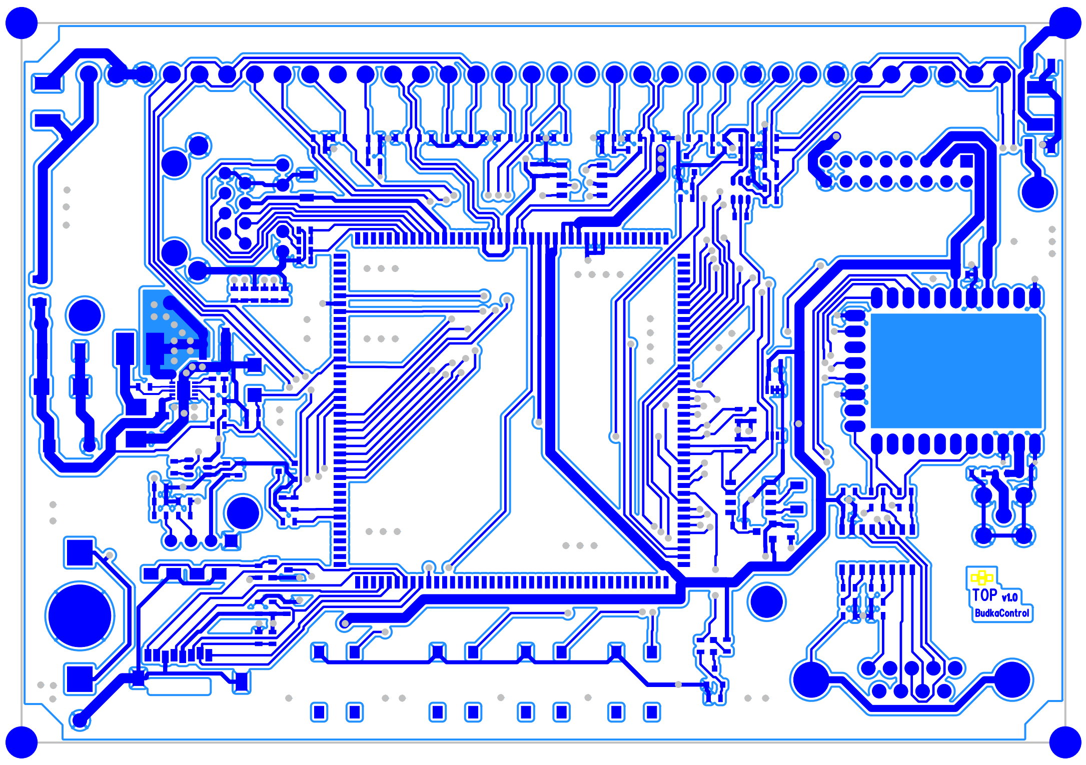


Figure 47. Board routing layer top.

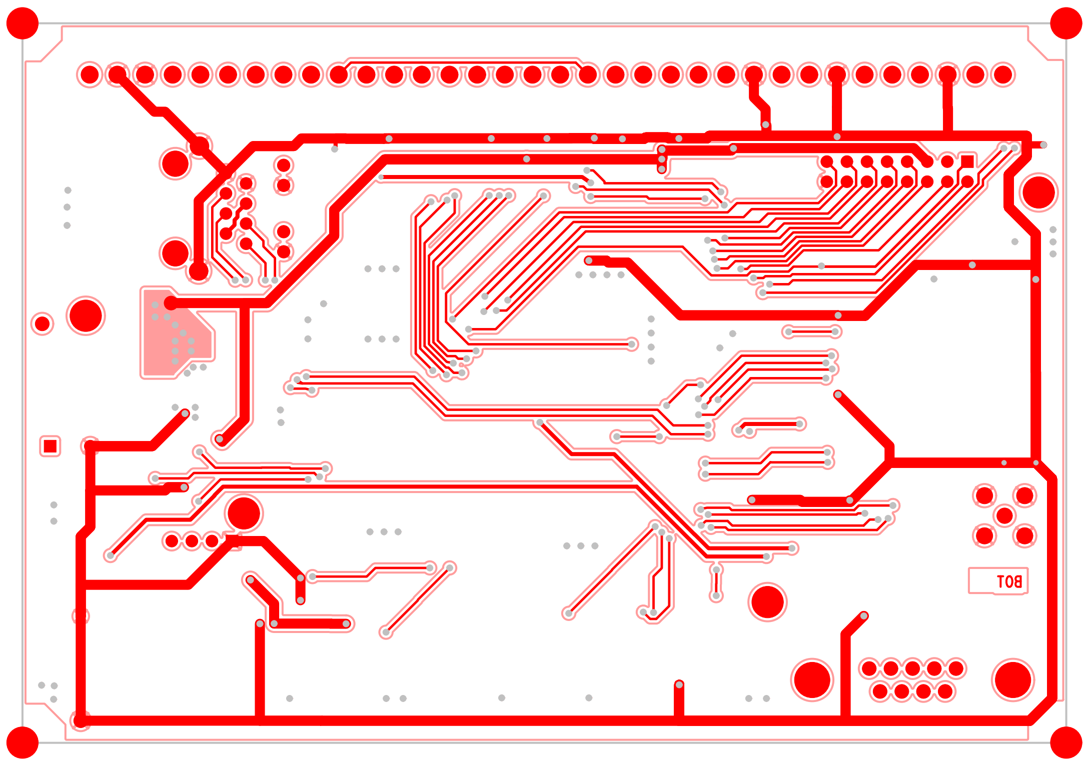


Figure 48. Board routing layer bottom.

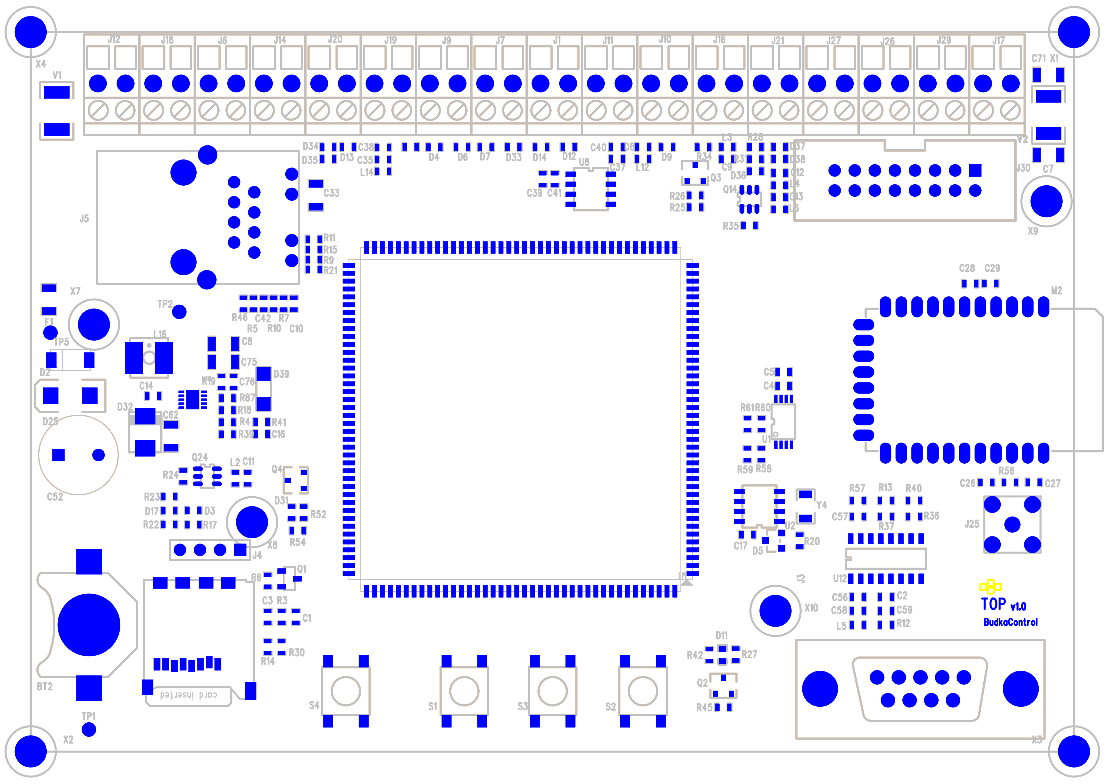


Figure 49. Silkscreen layer top.

C.2. BudkaLighting

Routings and silkscreens of the camera infrared lighting board named *BudkaLighting*.

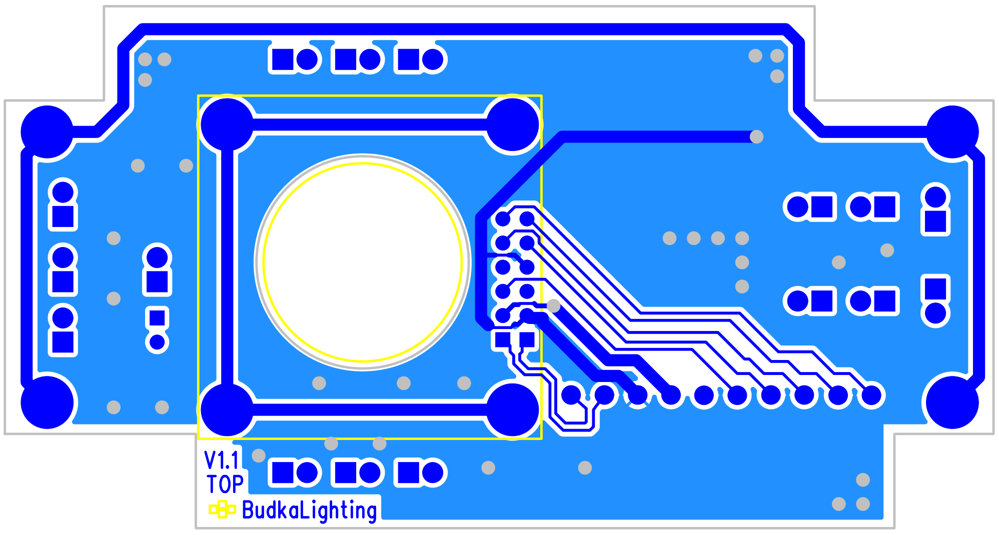


Figure 50. Board routing layer top.

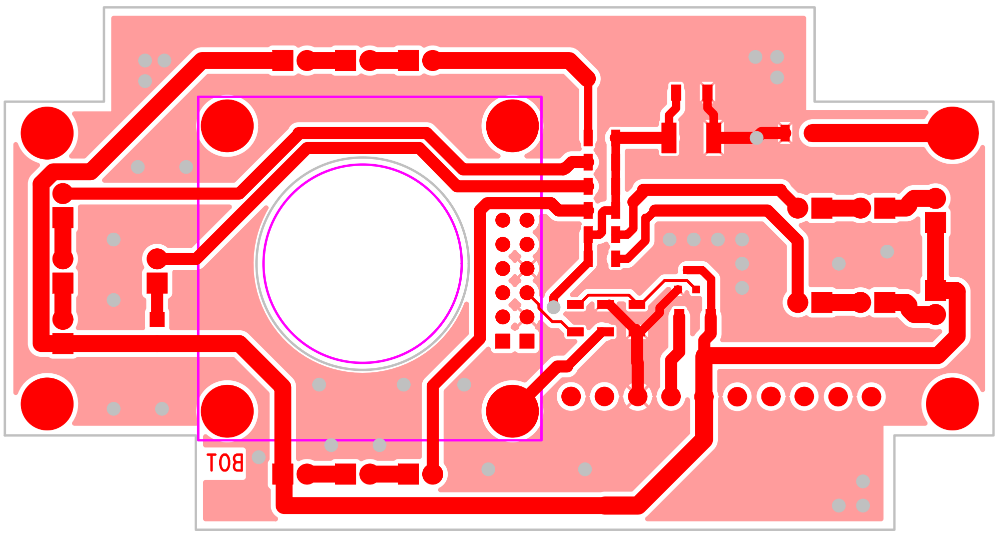


Figure 51. Board routing layer bottom.

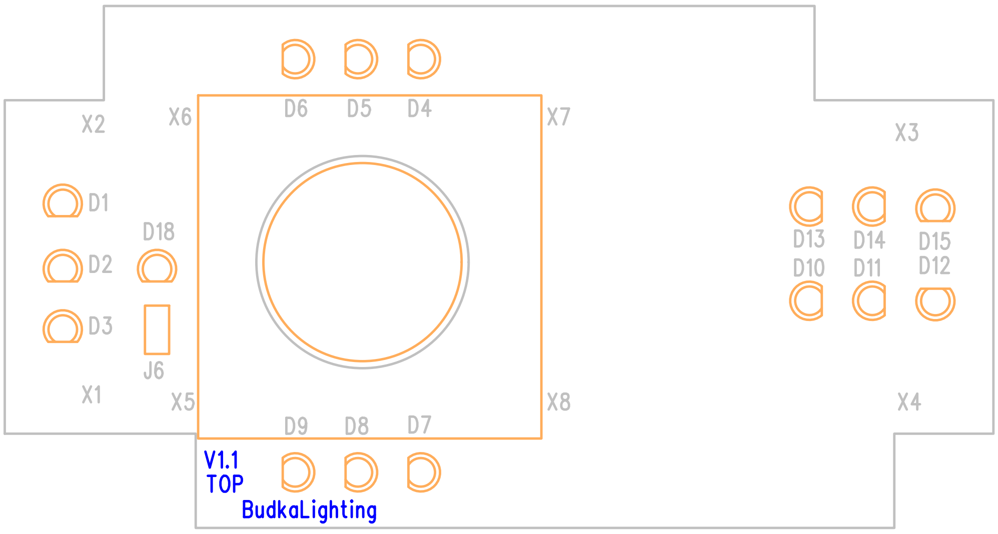


Figure 52. Silkscreen layer top.

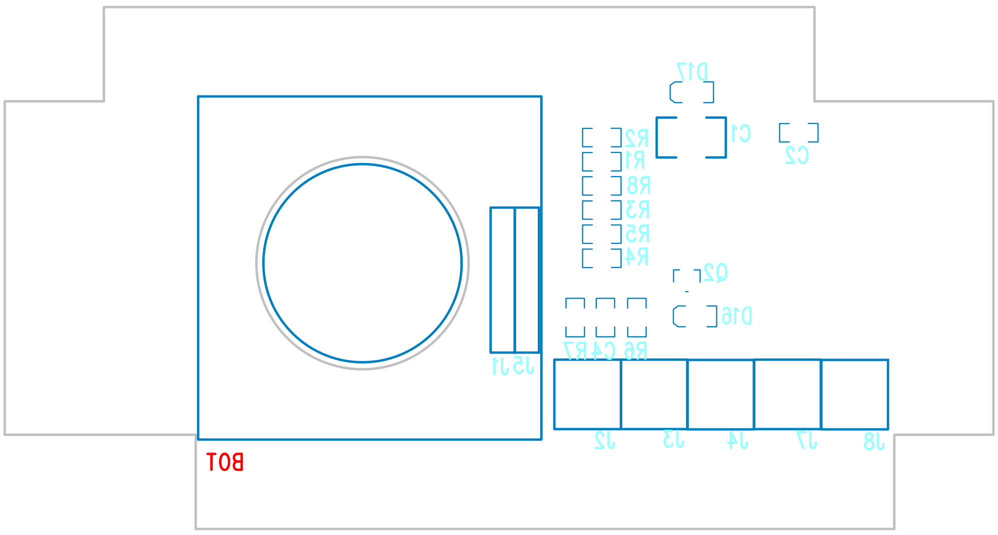


Figure 53. Silkscreen layer bottom.

C.3. BudkaIRBar

Routings and silkscreens of the infrared light barrier board named *BudkaIRBar*.

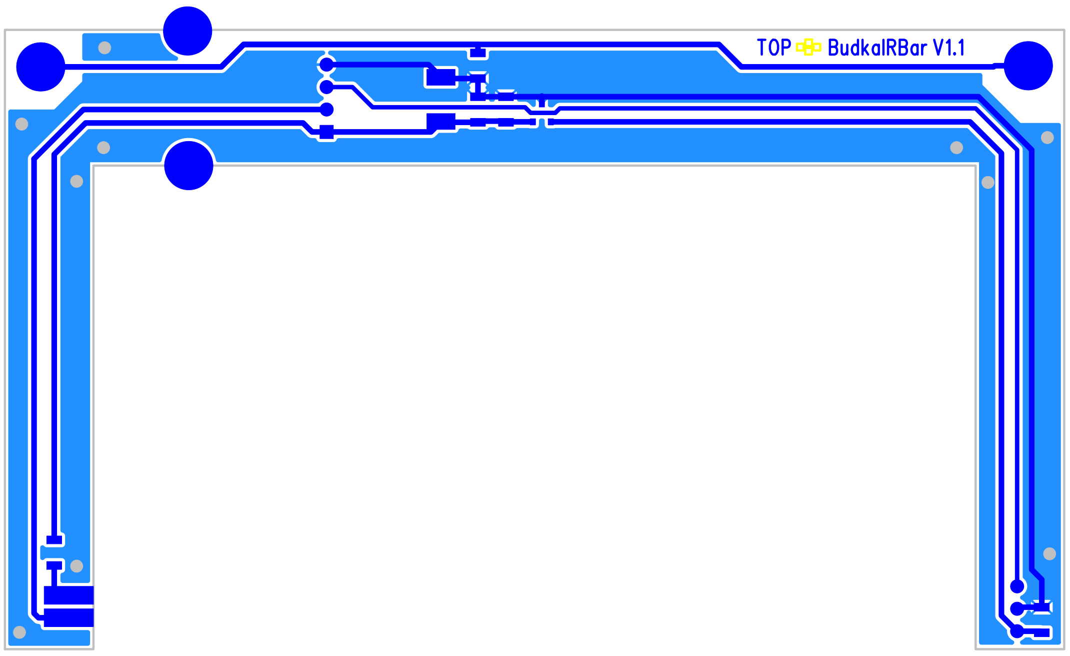


Figure 54. Board routing layer top.

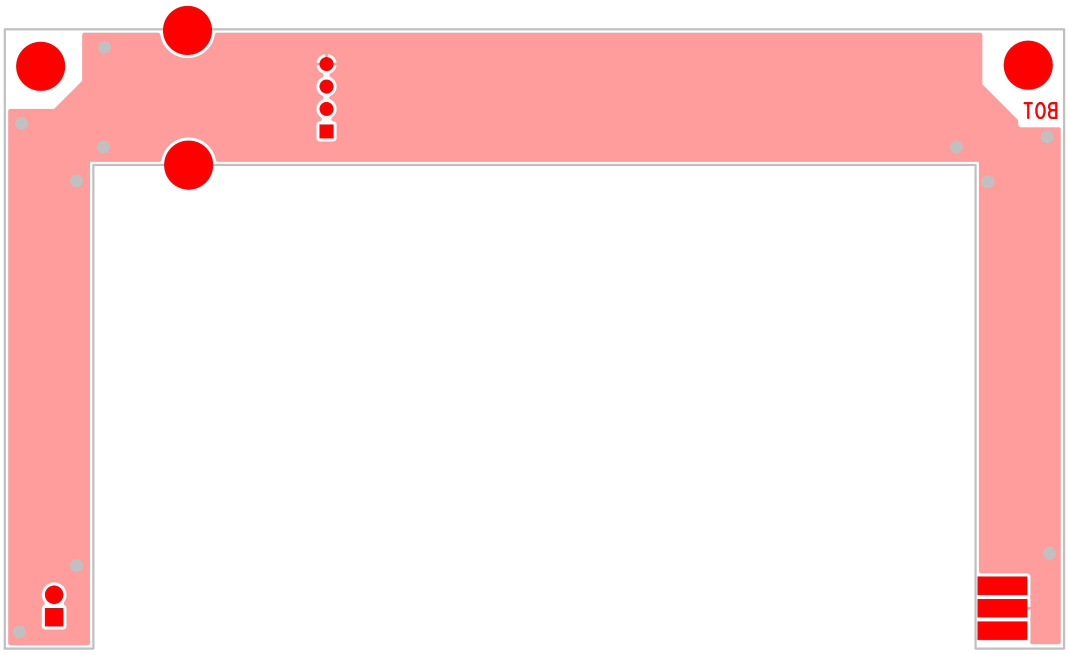


Figure 55. Board routing layer bottom.

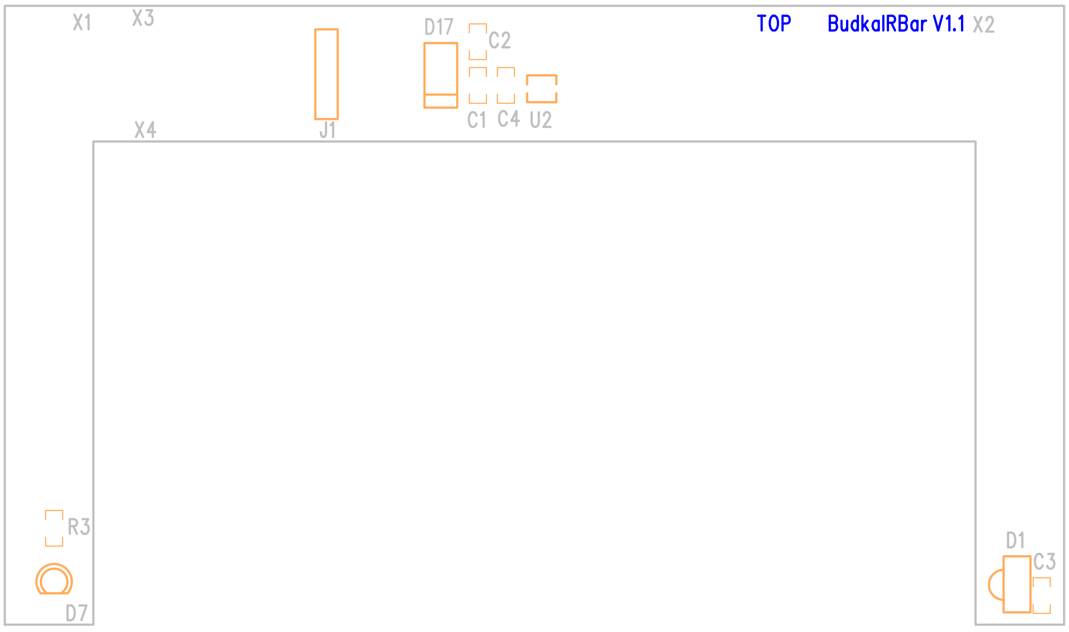


Figure 56. Silkscreen layer top.

C.4. BudkaLTS

Routings and silkscreens of the temperature and light sensors board named *BudkaLTS*.

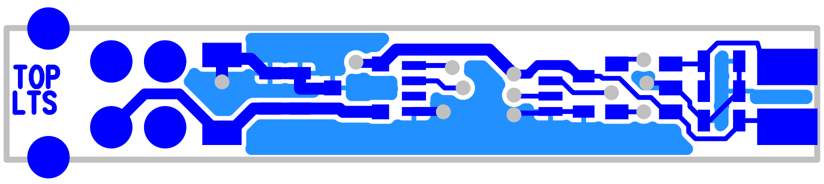


Figure 57. Board routing layer top.

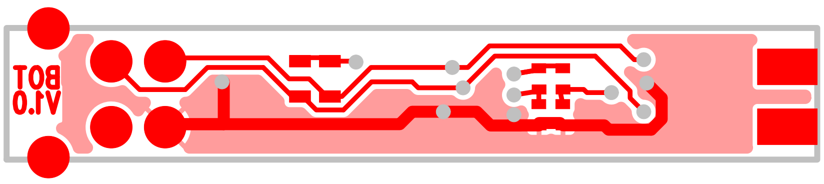


Figure 58. Board routing layer bottom.

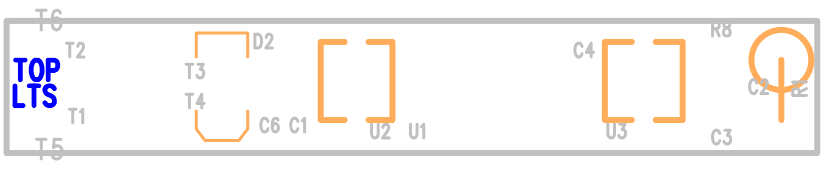
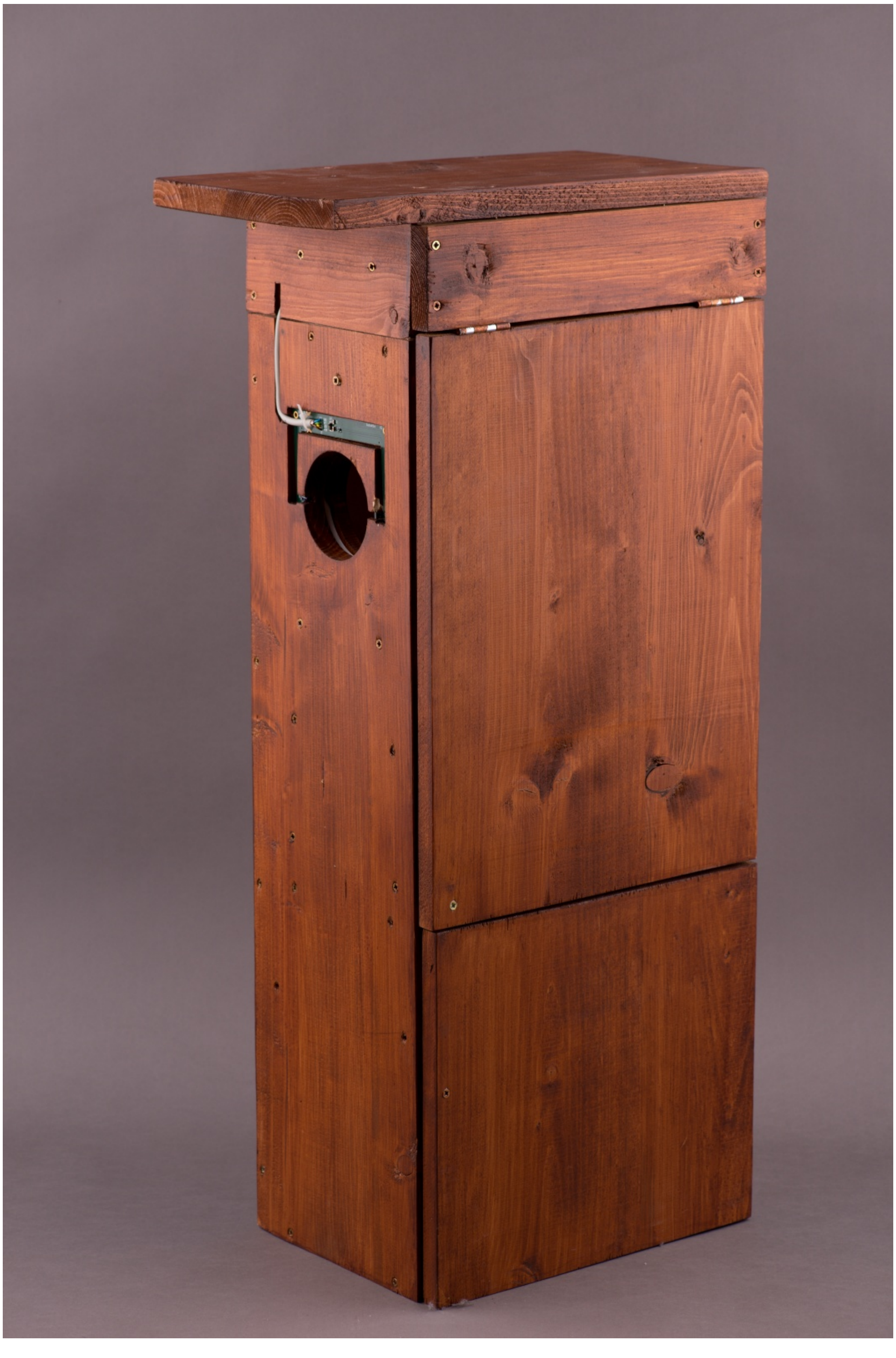


Figure 59. Silkscreen layer top.

Appendix D.

Photographs

Photographs of the nest-box and its components.



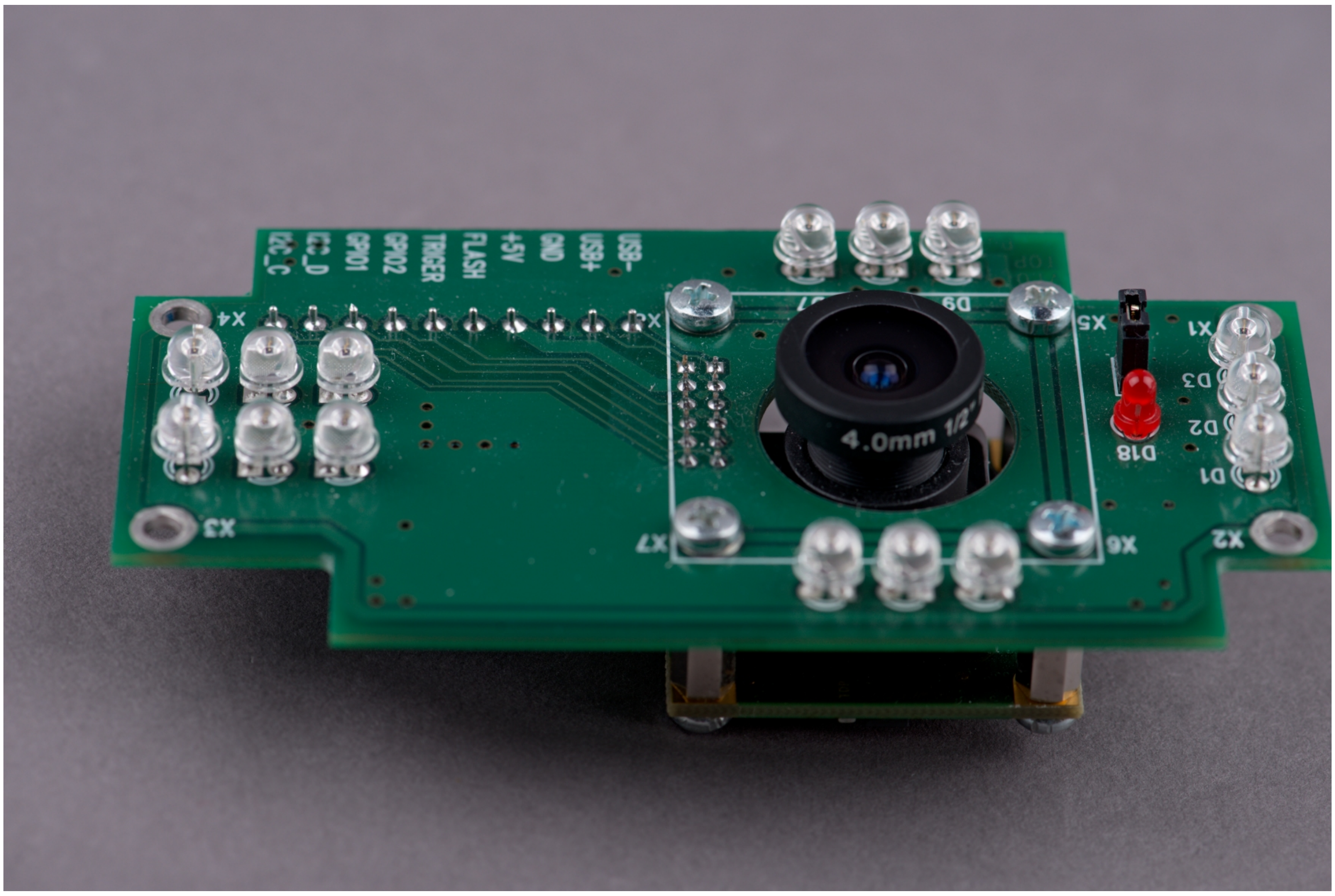


Figure 60. *BudkaLighting* board with attached camera.

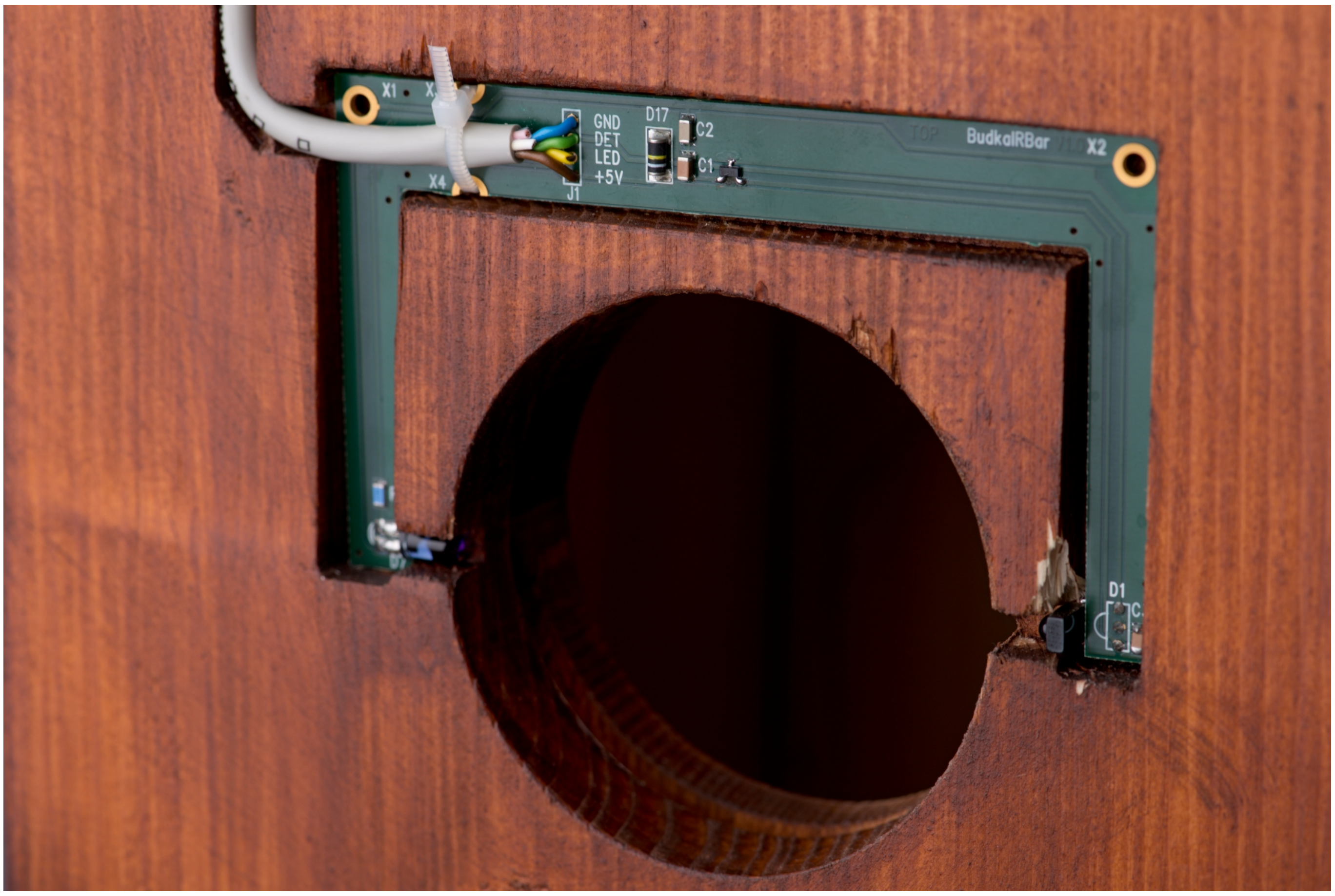


Figure 61. *BudkaIRBar* board installed in the nest-box.

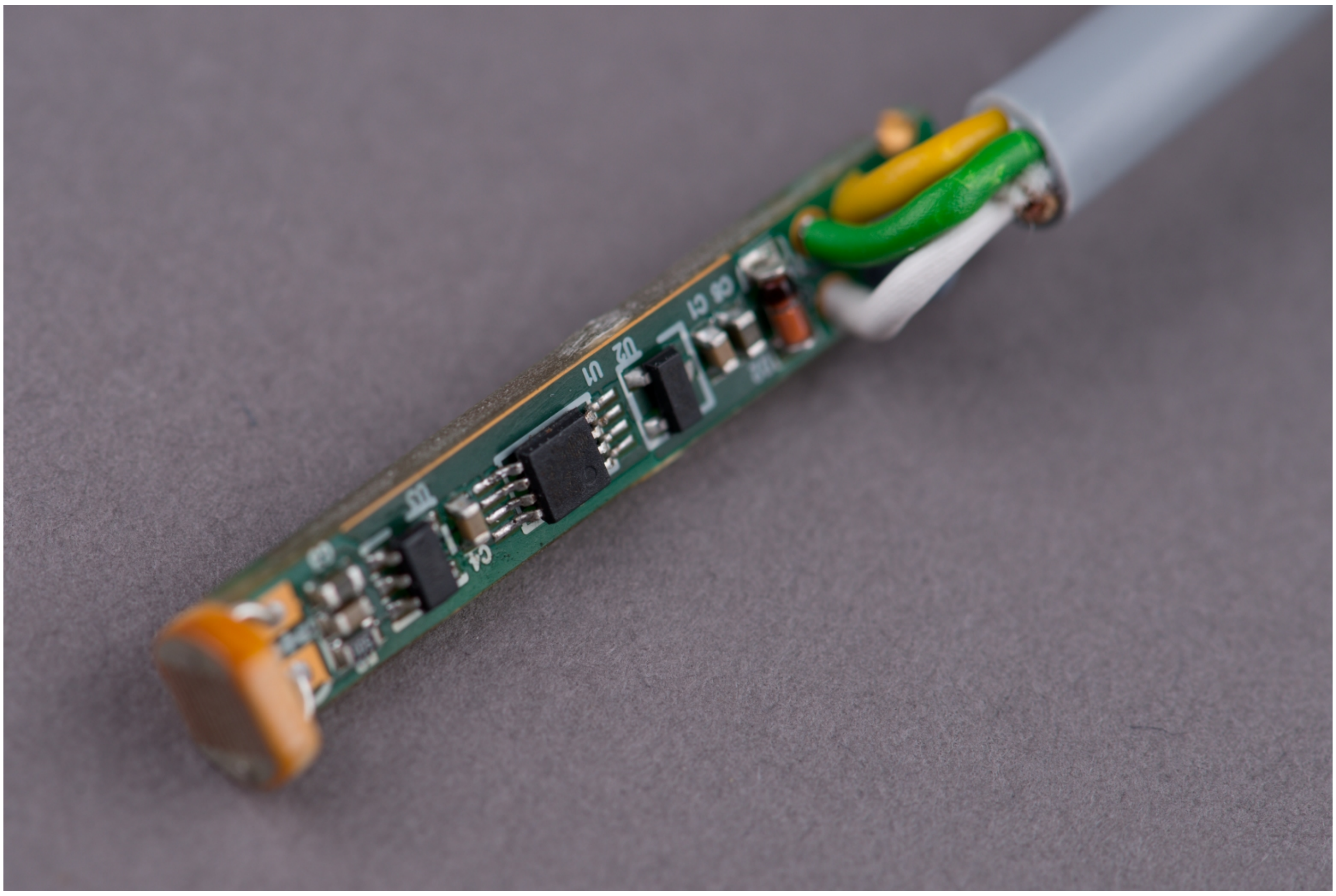


Figure 62. *BudkaLTS* board (variant with the light sensor).

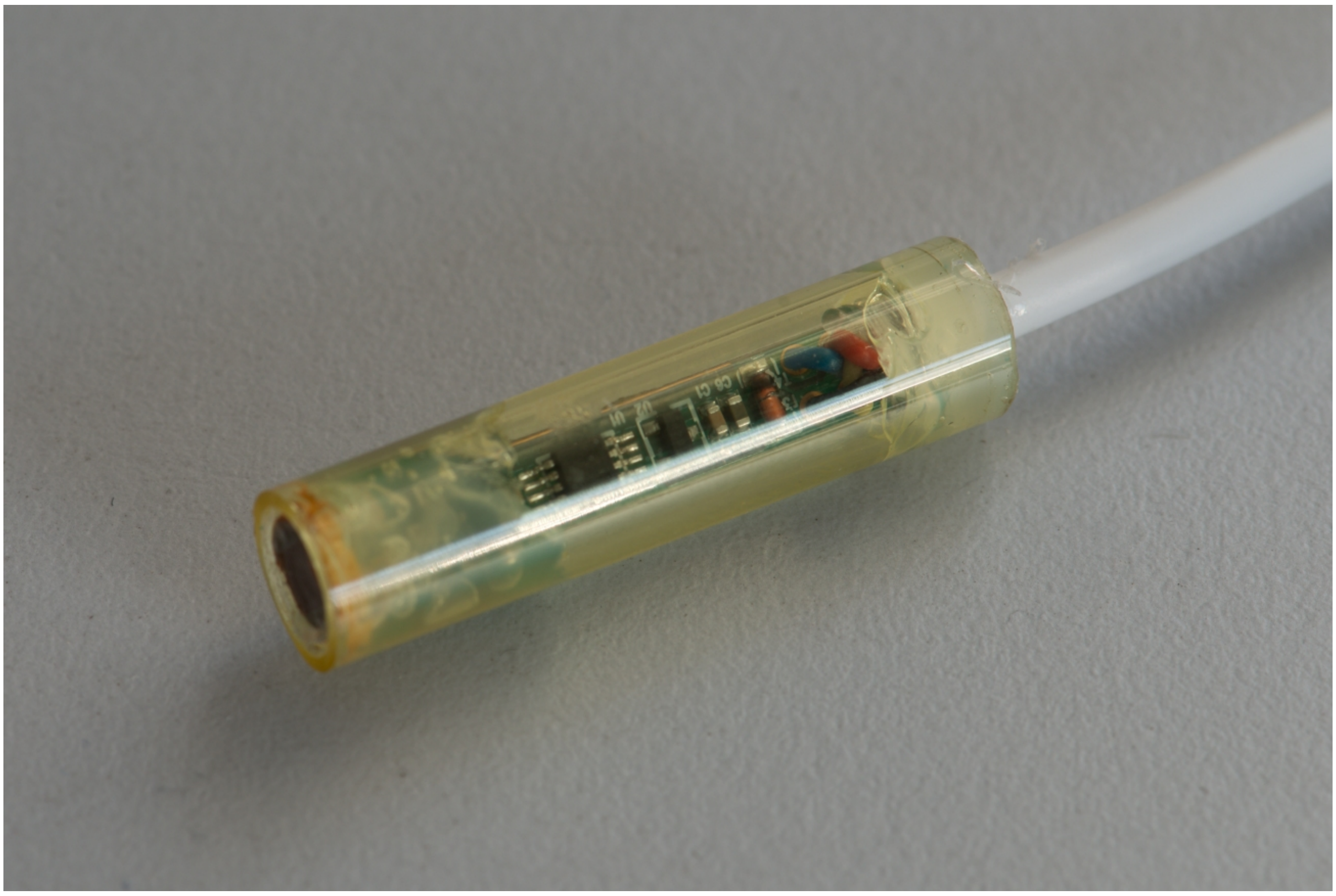


Figure 63. *BudkaLTS* board closed in a cover.

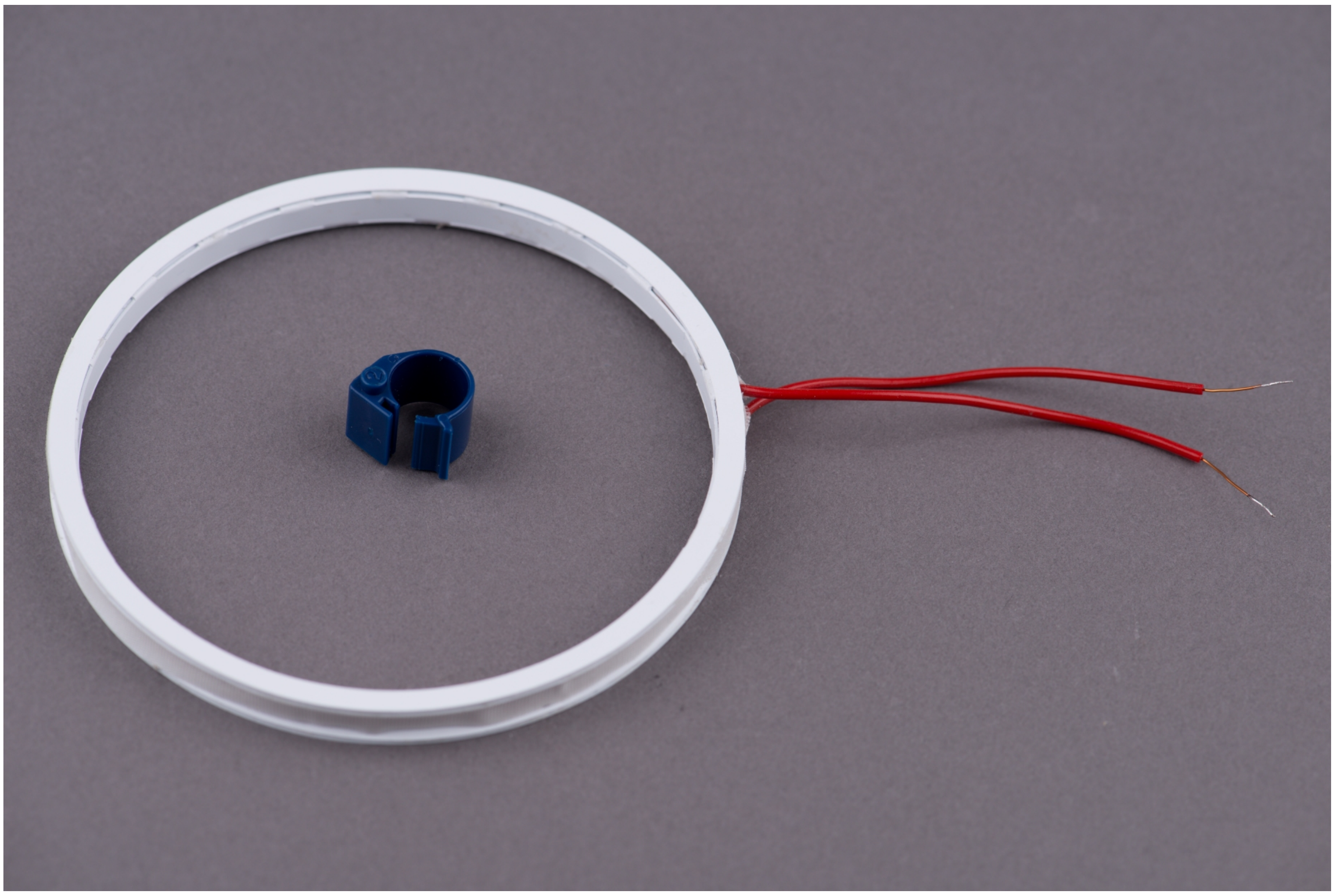


Figure 64. RFID antenna and the PIT chip.

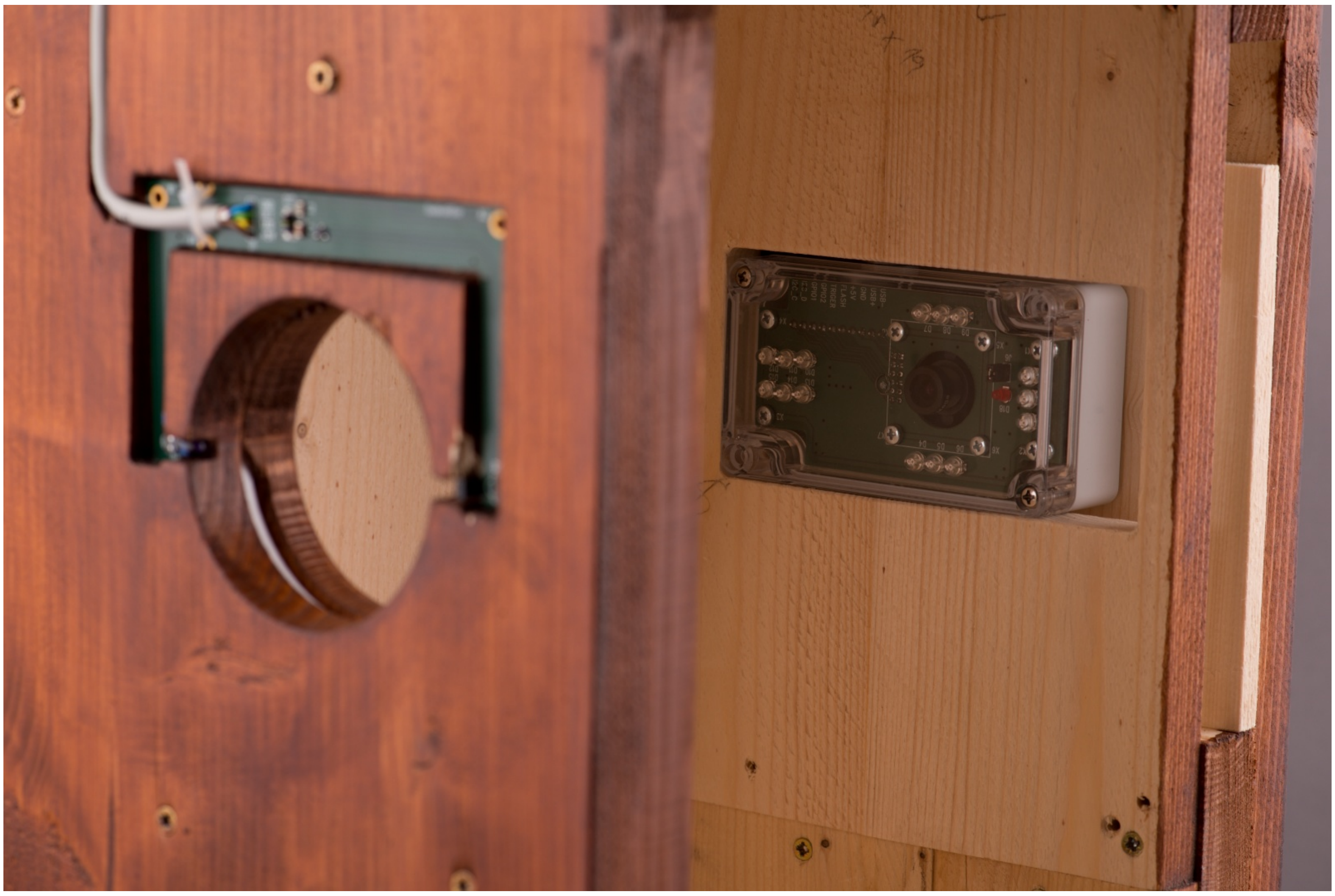


Figure 65. Installed *fly-in* camera, light barrier and RFID antenna.

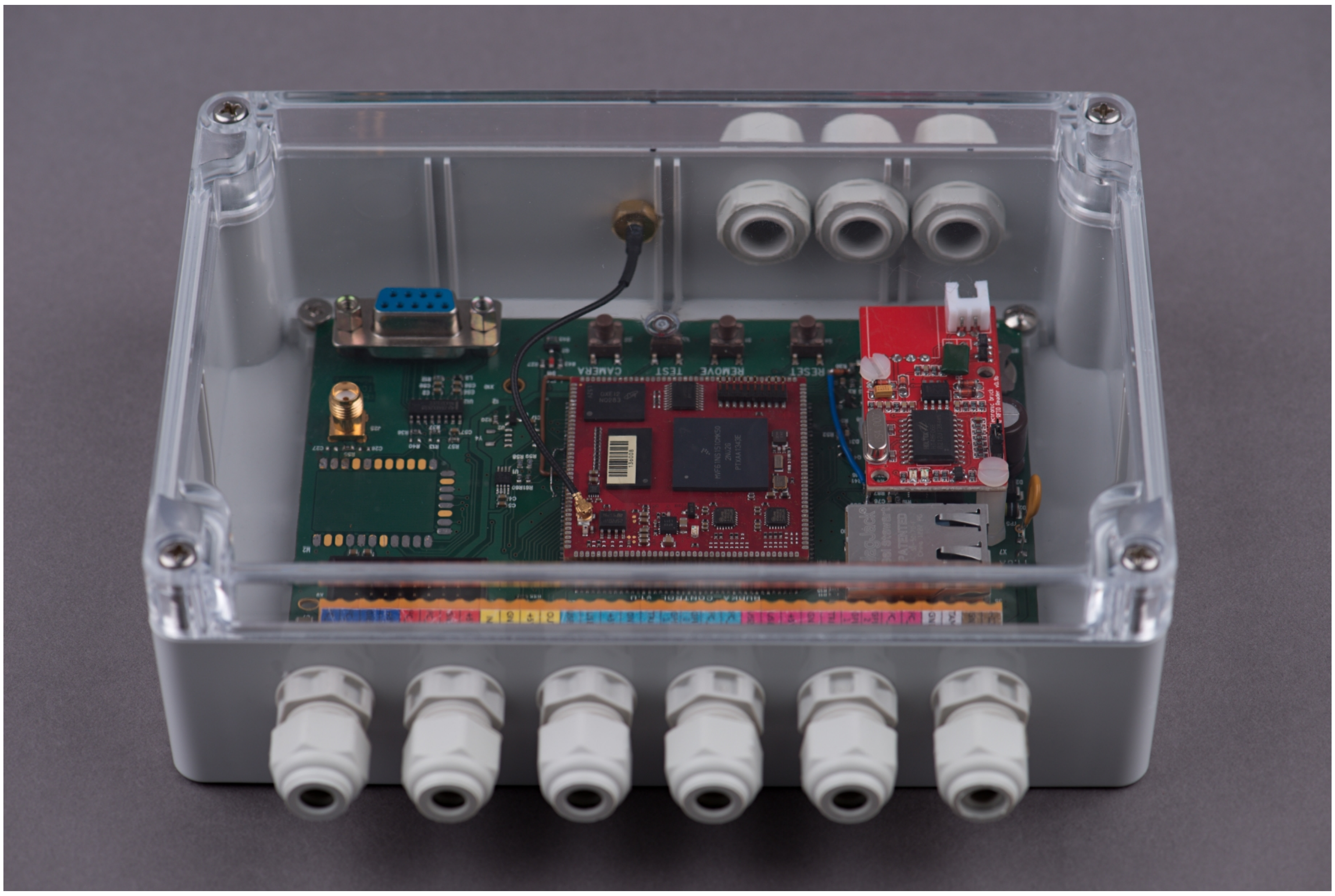


Figure 66. *BudkaControl* board covered in the covering box.

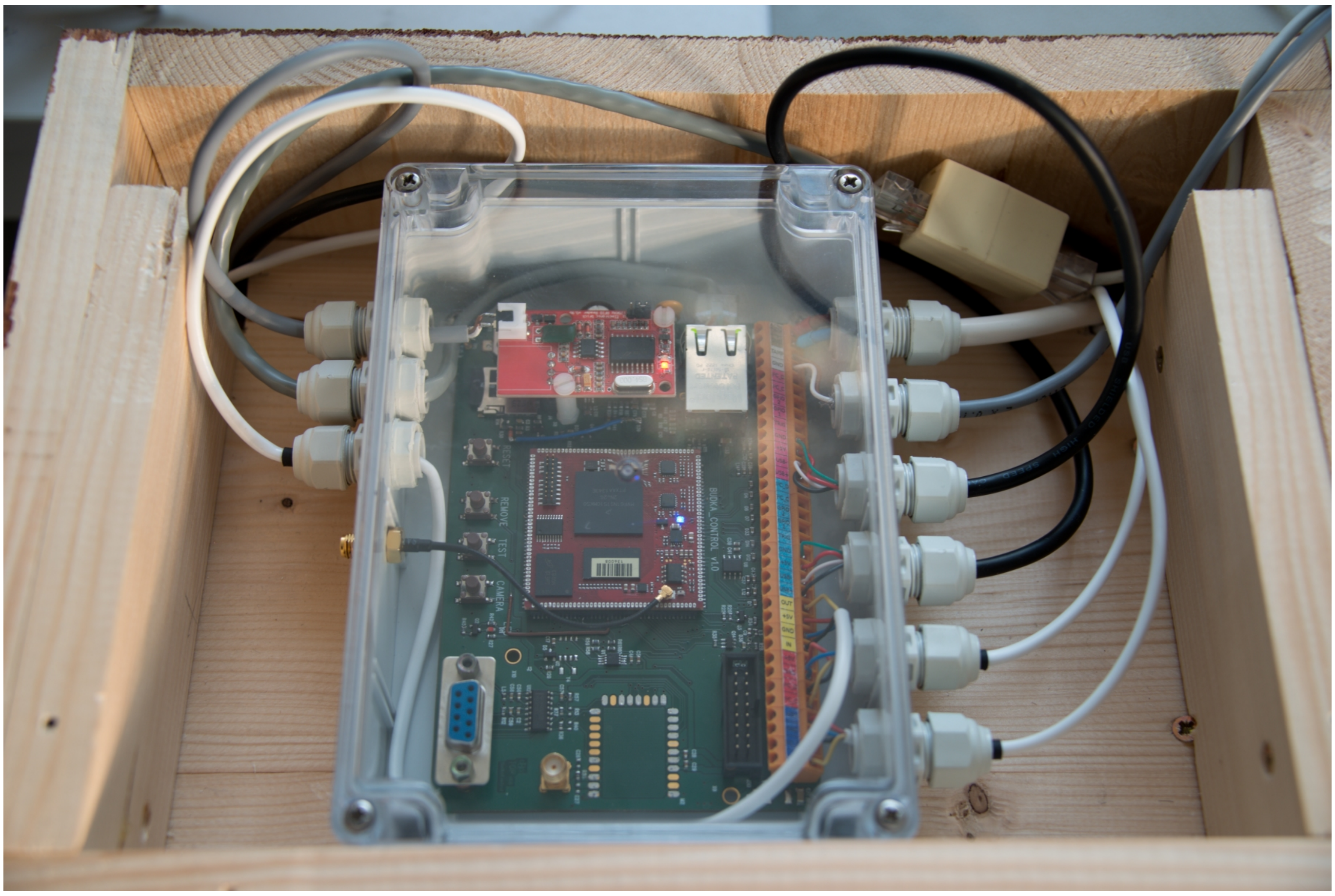


Figure 67. *BudkaControl* board installed in the nest-box.

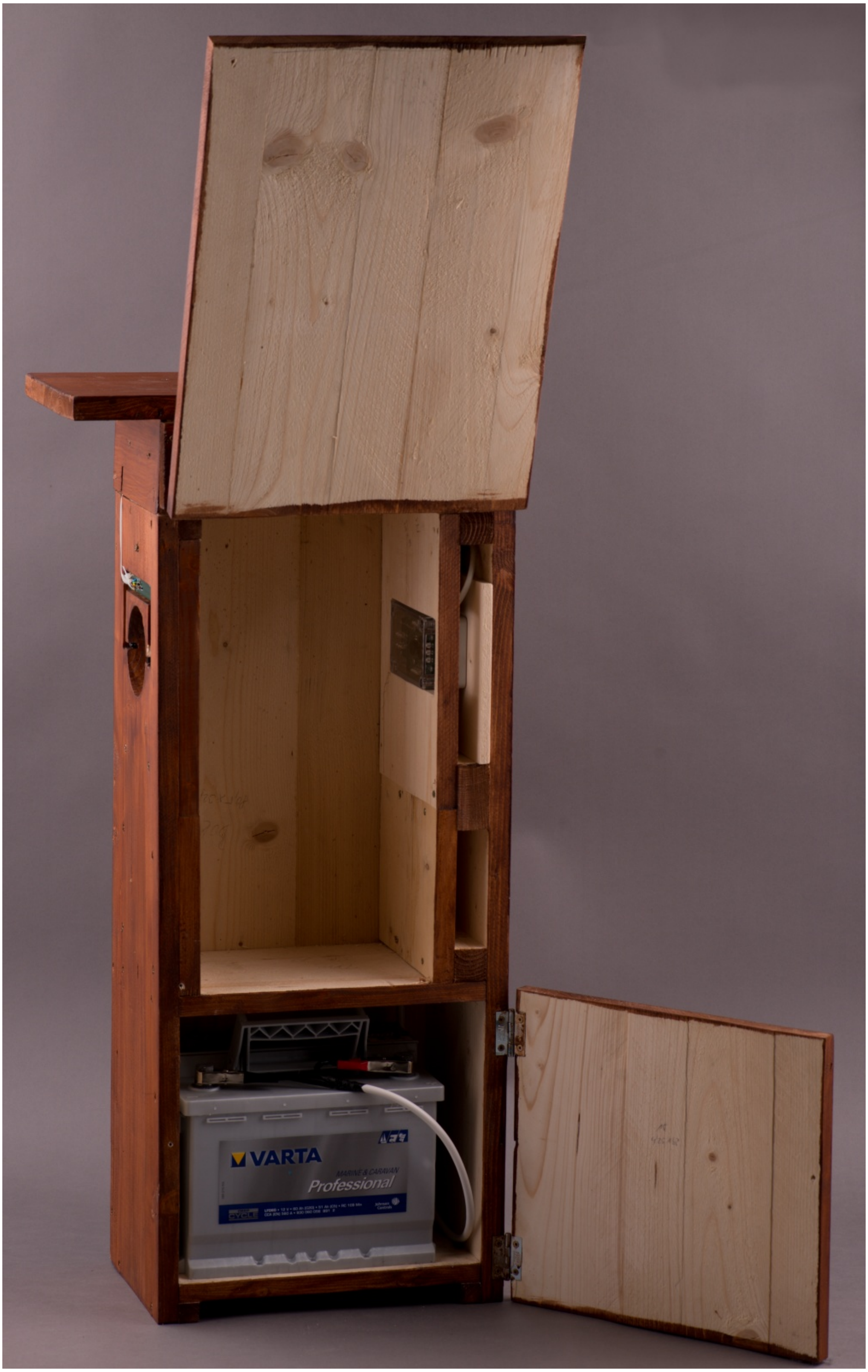


Figure 68. Complete view on the intelligent bird nest-box.