Proposal of Electronic Tag for Monitoring Environmental Conditions During Product Transportation

Mikhaylov Dmitry, Smirnov Alexander, Khabibullin Timur, Froimson Mikhail, Zuykov Alexander, Sychov Nikolay, Grigorenko Andrey and Tolstaya Anastasia
Youth Engineering Centre of the National Research Nuclear University "MEPhI", Kashirskoye shosse 31, Moscow, Russian Federation

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Abstract: The present invention is directed to an electronic tag for monitoring transportation of goods over long periods of time. It provides monitoring of all data regarding environmental conditions (for example, if an item should not be stored at more than some critical temperature, but had remained the entire time at just below the critical temperature, this also might be of interest). The tag reading device can communicate with the tag via a wired or wireless interface to transmit the data about conditions violations and display this information on its screen or forward it further to a PC or to a local area network. The paper provides the information about choice of the required for the system electronic components, tag, tag reading device, system software, monitoring methods, additional options, and system testing. The tag temperature registration accuracy is ± 0.5^0C.

1 INTRODUCTION

Delivery logistics is one of the most risky periods of many products' lifetime. A lot of products or components have serious restrictions on the environmental conditions, e.g., on temperature (drugs, food), humidity (electronic components), vibration (electronic devices, fragile objects), etc. For example, period of validity of medicinal agent depends on physical, chemical and biological processes therein. These processes are greatly influenced by humidity, light intensity, pH, and temperature. (Kazakova O., 2010; Register of medicines of Russia radar RLS+, 2004) As such, the problem of monitoring conditions during product transportation and delivery exists.

Some conventional solutions exist, such as placing drugs in special cases with almost constant temperature, placing electronic components in vacuum packets, etc., but a mechanism for monitoring the transportation conditions is still of great need.

There are a number of such mechanisms – temperature sensors in the containers for transporting medications, humidity papers that change color when humidity restrictions are violated, etc. (Temperature recorder DS1921L-F51, et., 2014; Disposable temperature indicators WarmMark, 2013; Temperature recorders (loggers), 2012). Several papers have been devoted to this issue – they may be considered as analogs of the proposed monitoring device called BBT (Wang Jiahan, 2011; Chen-Ming, 2012; Meng Xian-Yao, 2009; Wang Keliang, 2010; Chenxia Yun, 2009). However, all of the conventional solutions have a number of limitations.

For example, container temperature monitoring systems do not guarantee that the temperature restrictions are not violated when the medications are taken out of the container and placed in a warehouse. Humidity monitors cannot give any information about the time and duration of violation of storage and transportation conditions. Finally, in some cases they have low memory.

Another important sphere is transportation and storage of unstable chemical substances such as hydrogen in a liquid form. (Saturation Properties for Hydrogen – Pressure Increments)

Accordingly, there is a need in the art for a more reliable and robust system and method for monitoring environmental conditions during transportation of goods.

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2 SYSTEM FOR MONITORING ENVIRONMENTAL CONDITIONS

The invention addresses the need for monitoring environmental condition during the transporting of goods.

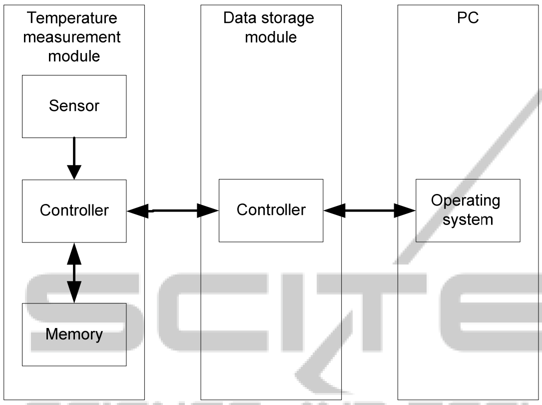

Figure 1: General system scheme.

The solution includes a thin electronic tag with autonomous power, and a tag reading device as well as special software for a personal computer (PC) (Fig. 1).

2.1 Choice of the Required Electronic Components

2.1.1 Microcontrollers

Consider the basic specifications (see Table 1) of controllers that can be used for a proposed system. The chip is selected according to these specifications and the presence of temperature sensor in microcontroller.

According to Table 1 microcontrollers STM32F100C4T6B and MSP430F2101IPW28 for data collection module and temperature monitoring module respectively. The main parameters influencing the choice were amount of memory, processor speed and power consumption.

2.1.2 Non-volatile Memory

EEPROM (Electrically Erasable Programmable Read-Only Memory) 24aa128 (24AA128/24LC128/24FC128, 2004) is a tag non-volatile memory for temperature data storage. EEPROM 24aa128 allows the following temperature ranges: industrial: -40°C to +85°C; automotive: -40°C to +125°C. In comparison with Flash EEPROM 24aa128 has longest storage time, lower power consumption in sleeping mode and while recording, more rewriting cycles.

2.2 Tag

The tag should be slim enough to be inserted into a product’s box or a container before sealing. The BBT tag monitors the environmental conditions with particular sensors (for example, temperature sensor, humidity sensor, pressure sensor, accelerometers, some combination of these, etc.) and logs all detected violations of the monitored conditions with timestamps into its non-volatile memory.

Alternatively, all data regarding environmental conditions during the transportation and delivery can be monitored. For example, if the item should not be at more than some critical temperature, but had remained the entire time at just below the critical temperature, this also might be of interest.

The system operates in the following way (by the example of temperature registration). The monitoring tag records temperature inside the monitored volumes in the range of minus 20°C to

Table 1: Basic specifications of microcontrollers (LPC1111FHN33, 2014; STM32F100x4, 2012; ATtiny13A, 2012; ATmega48/V, 2011; MSP430F2101IPW, 2004; PIC16F676, 2014; PIC12F509, 2009; PIC10F200, 2013).

Microcontroller	Core	Price (RUB)	Flash-memory (kb)	RAM (kb)	Processor speed (MIPS)	Energy consumption in optimal mode (mA)
LPC1111FHN33	ARM 32-bit Cortex M0	100	8	2	40	8
STM32F100C4T6B	ARM 32-bit Cortex-M3	78	16	4	30	8
AtTiny13A	Atmel 8bit	70	1	0.064	20	11
atmega48	Atmel 8bit	80	4	0.5	20	11
MSP430F2101IPW28	TI 16bit MSP430	70	8	0.5	16	3
PIC16F676	PIC16 8bit	60	2	0.22	5	0.4
PIC12F509	PIC12 8bit	60	2	0.041	5	0.4
PIC10F200T	PIC10 8bit	40	0.25	0.016	1	0.2

50°C with pre-mechanical (LED) alarm temperature points 0°C, 2°C, 8°C, 10°C, 15°C, 25°C, and documentation of the entry in the non-volatile memory. Quantitative values of temperature registered in the calendar view and in real time form in temperature-time schedules are sent to a personal computer using a special USB-device. The software should allow recounting total affecting temperature into heat calories.

The tag provides the following operation modes:

- sleep mode – thermo-sensor is not active, there is no registration and the tag is ready to receive commands to turn on;
- operating mode – thermo-sensor is active, the tag powered by the starting device is working in the recording mode. Registered data are stored in non-volatile memory in encrypted state and until reading the information is stored in an inaccessible area of the memory;
- LEDs triggering on 0°C, 2°C without counting temperature calories.

The tag includes the following components shown in Figure 2.

A battery is a “tablet” battery of any radius (or custom manufactured to an arbitrary shape). The type of battery is chosen by the expected drain of the device and its lifetime. If a wireless channel is used, and the tag is expected to function about 2-3 years, a lithium element battery is applied.

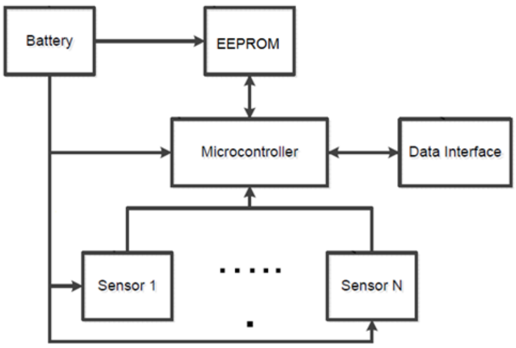

Figure 2: A schematic diagram of the tag.

If only a wired interface is used and the tag lifetime is about half a year, a less expensive NiCd battery can be implemented. Alternatively, a super-capacitor also can be applied. Typical battery parameters are 1.6-3.3 V, 50 mA maximum output current, 150 mAh. The battery parameters can be sacrificed, for example, if a smaller tag is needed (and other reduced parameters are acceptable, such as fewer measurements per unit time).

Non-volatile memory is used to store a tag log of the monitored conditions (temperature, humidity, etc). The log typically contains:

- tag serial number;
- tag-related data (i.e., a tag activation time, tag manufacturing date, etc.).

The log data entries can be, for example:

TIMESTAMP1 – SENSOR1 MEASURE1 – SENSOR2 MEASURE1 … – SENSOR N MEASURE1

TIMESTAMP2 – SENSOR1 MEASURE2 – SENSOR2 MEASURE2 … – SENSOR N MEASURE2

A microcontroller (MCU) is used to:

- acquire data from the sensors;
- store the data into non-volatile memory;
- acquire data from non-volatile memory;
- send data via data interface.

The non-volatile memory can be embedded into the microcontroller.

Sensors can be an integrated circuit or other kind of device, with digital or analog output that converts any physical parameter (temperature, humidity, pressure, etc.) into voltage (analog) or code (digital). This can be a thermocouple (a temperature sensor based on the Seebeck effect (Encyclopedia of Physics, 1998)), a humidity sensor (capacitive, resistive or any other type), a pH sensor of any kind (based on potentiometer, ion-sensitive field-effect transistor, or on any other principle), an accelerometer and a gyroscope (such micro-electromechanical systems, capacitive accelerometers, etc.), etc.

The sensors measure the value with the required accuracy and should stay alive under any possible conditions during the transportation. The sensors can be embedded into the microcontroller.

A data interface is a communication channel between the tag and the devices around it. The data interface can be either wired or wireless.

A wireless data interface allows for communicating with the tag during the entire period of delivery, sending commands, reprogramming the tag, reading data, etc. It is very helpful for different logistic operations. The whole shipment might be thrown away, if the tag data shows that the required environmental conditions had been seriously violated.

The main disadvantage is that it consumes a lot of battery power and it significantly increases the cost of the device. A wired interface, on the other hand, does not allow communicating with the tag when it is “in the box.” It can only be activated, placed with the goods, and checked to see what was going on with the shipment when it is unpacked. The advantage is that it is less expensive.

Both interfaces could be implemented inside the processor (there are processors with the wireless communication features) or by using an external interface controller. The wireless interface can use either an open or proprietary protocol. The wired interface can be custom made, I2C, SPI, SD, iButton, etc.

Consider the temperature monitoring module (Figure 3).

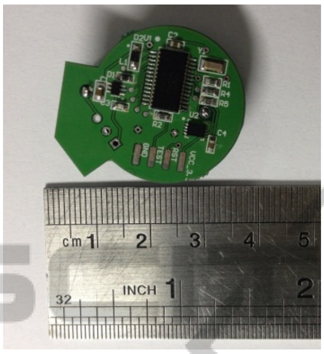

Figure 3: Temperature monitoring module.

The system is likely to be the least expensive one (less than 1$ per unit in 1000-pieces shipment), the lowest active drain (hundreds of mA in active mode), the lowest frequency (in most cases, 32 kHz as the main clock is sufficient), the lowest pin-count (if an external non-volatile memory is not used and the communication interface is wired, it can even be an 8-pin integrated circuit).

2.3 Tag Reading Device

The tag reading device can communicate with the tag via a wired or wireless interface to transmit the data about conditions violations and display this information on its screen or forward it further to a PC or to a local area network (LAN).

The reader includes the following components shown in Figure 4.

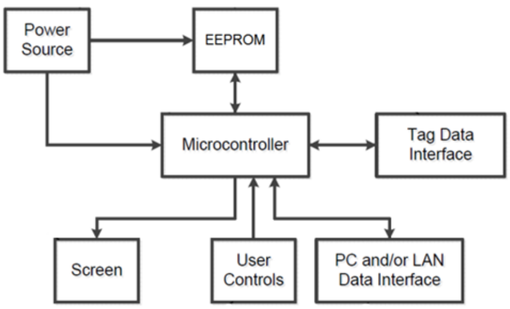

Figure 4: A schematic diagram of the reader.

A power source is a standard battery form-factor (AA, AAA, one or more), can be a re-chargeable battery, can be an accumulator cell (replaceable or not). The power source can be a super-capacitor. The battery can be charged via AC/DC (alternating current/direct current) adapter, DC/DC adapter, USB connection or wirelessly, by vibration or through by heat (thermocouple).

The non-volatile memory is used to store data from tags, so its capacity is at least:

N * TagRAMCapacity,

where N is the number of tags the reader obtains data from.

The non-volatile memory can have its file system, based on commonly used (FAT, NTFS, etc.), or based on proprietary standards.

The microcontroller acquires data from tags via a tag data interface and stores it in the non-volatile memory. The microcontroller monitors user controls and performs certain actions (read tags, calibrate time, etc.). The microcontroller obtains data from the memory and sends the data via PC/LAN interface.

The tag data interface is an interface compatible with the tag's data interface. A screen is used to output information to the user. The screen can be very small (1 or 2 inches diagonal) to minimize the reader's overall size or the screen can be rather large (about 10 inches in diagonal) to maximize usability. The screen can be combined with a touch panel based on any technology (resistive, capacitive, infrared, SAW, etc.) that plays a part of user controls. The screen can also have some display connection (HDMI, DVI, VGA, DisplayPort, etc.) to the external display.

User controls are any buttons, touch screen menus or triggers. The buttons can have pre-defined functions (i.e., read tag, clear non-volatile memory, set tag’s clock, etc.), or the buttons can be used to navigate through the device's menu (Up, Down, Forward, Back).

PC and/or LAN interface is used to translate data from non-volatile memory to computer or computer network. The interface can be wired or wireless. For example, USB, Ethernet, Wi-Fi, Bluetooth, etc. can be used. In addition, the memory can be embedded into the microcontroller.

Consider the reading device (Figure 5).

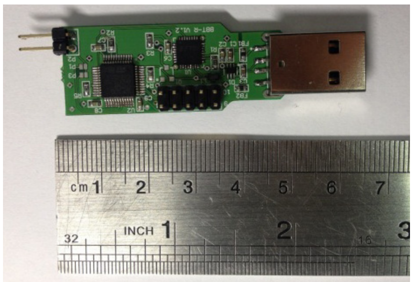

Figure 5: Reading device.

2.4 Monitoring Methods

If the tag measures data periodically, the tag only needs to store the activation time. If the tag logs only the times of violation of the allowed conditions, the timestamps are used.

The amount of non-volatile memory is determined by a predicted number of measurements taken during the tag's lifetime and the size of the measurements. For example, if a temperature is monitored (about 12 bits per measurement is needed) and the measurement is taken once a minute, then a one-year-long log will take up about 780 Kbytes of memory.

If only violations (for example if temperature is higher than 10^0C or lower than – 5^0C) are stored, then the additional 6 bytes of timestamps for each measure are used resulting in a total of 60 bits per measure. However, the conditions are expected to be within normal range during most of the transportation time. Thus, much less data is actually stored in the memory.

A rough guideline is that if conditions are logged every minute or so, then about 1 Mb per one sensor installed on the tag per one year of its lifetime is needed. Another concept of logging environmental conditions that significantly reduces the amount of used memory is not to log the measure every minute, but to store the "overall violation" data instead.

For example, a parameter should stay at or below A1, but it was violated and the value was A2 at one of the measures and then, returned to normal on the next measure. The measure is periodic and the time between two measures is D. Therefore, in the worst case, the duration of violation was about 2*D. The overall violation can be estimated as:

(A2 – A1) * 2 * D

– the violation value multiplied by the duration of the violation. Such estimate can be used to decide if the product can still be used, but it will not store the information of when a particular violation had occurred.

The two of the above methods can be combined. For example, the tag can know every time that it is passed from one company in the delivery chain to another via a wireless interface, so it can log data as follows:

OVERALL VIOLATION ON DELIVERY STAGE 1 (an ID can be used to determine which company had delivered the goods at specific stage, this ID can be transferred when the next transportation stage begins)

OVERALL VIOLATION ON DELIVERY STAGE 2

…

OVERALL VIOLATION ON DELIVERY STAGE N.

This technique can significantly reduce the amount of memory used compared with every-minute-logging, but still lets the final recipient of the cargo or the insurance company know the specific stage of delivery when the conditions were violated.

2.5 Software

As a part of the proposed temperature monitoring system the special software has been developed. The algorithm of data acquisition module`s software performance is shown in Figure 6 and the algorithm of temperature monitoring module`s software is presented in Figure 7.

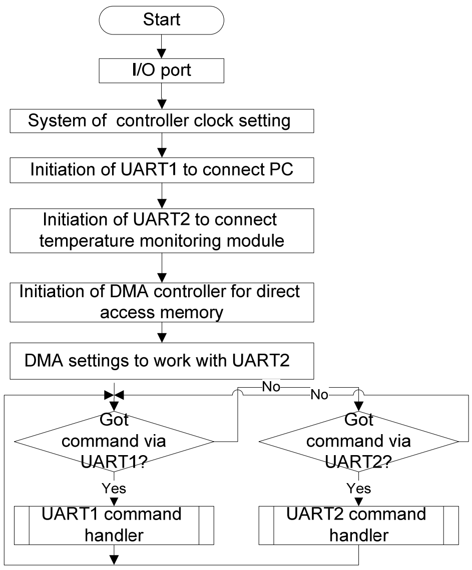

Figure 6: Algorithm of main cycle of data collecting module`s software.

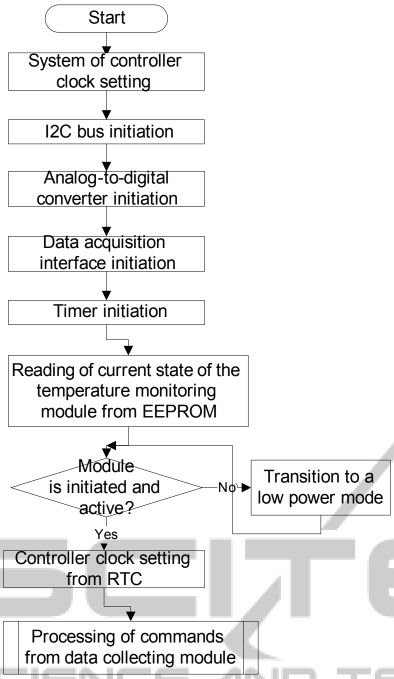

Figure 7: Algorithm of temperature monitoring module`s.

2.6 Testing

2.6.1 Sensors

The performance of the system with one temperature sensor was tested using a logic analyzer LeCroy Logic Studio 16 (LogicStudio™ 16 Channel Logic Analyzer, 2010). The tag was subjected to changing temperatures, obtaining the data. After they were read by the reader and transmitted to the PC, the data was analyzed by the software.

Obtained by the temperature monitoring module data can be analyzed in graphical interface of PC software as it is shown in Figure 8.

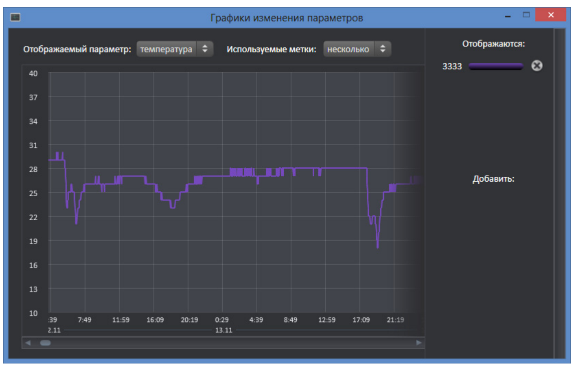

Figure 8: Temperature curve.

The testing of the tag accuracy was carried out using a sealed chamber with zero thermal gradient. The pre-calibrated tag was placed inside the chamber in which the temperature was changed every five minutes. The tag accuracy is ± 0.5^0C.

The linearity of the sensors allow after assembly to make a temperature measurement and store in the tag`s memory the difference between the measured temperature and the temperature obtained from the reference sensor.

To increase the sensor accuracy it is proposed to make the tag`s body in a way, shown in Figure 9.

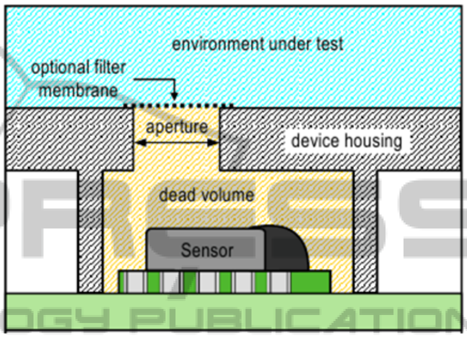

Figure 9: Proposed tag`s body (SHT21, 2011).

The testing of the humidity monitoring is now underway that is why the testing results are not presented in this paper.

2.6.2 Battery

For battery testing the battery with capacity I = 225 mA/h was taken. The aim was to check its life-time depending on the reference frequency (frequency of requests to tag). The results are shown in Table 2. Battery consumption diagram is shown in Figure 10.

2.7 Additional Options

As an option, an integration value of the violation condition over time can be stored.

In general, the tag can be used multiple times. A mechanism for charging tag's battery, erasing tag's non-volatile memory and calibrating tag's clock is provided. Memory damp can be performed as a command received via the data interface. Battery replacement can be performed if the tag's body has an appropriate battery slot.

Battery recharging can be performed, if the tag has a charging socket on it and a battery controller integrated circuit on the tag (this function can also be performed by the processor). The tag can also be recharged wirelessly using the alternating magnetic fields. Thus, the tag can be hermetically sealed.

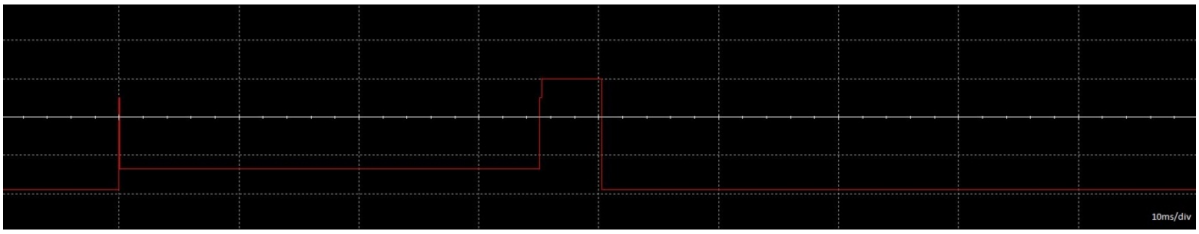

Figure 10: Battery power consumption diagram.

Table 2: Battery testing parameters and life-time.

T (reference frequency)	I (mA/h)	Operation time (s)	Operation time (h)	Operation time (days)
0.001	34.4500000000000	23512.34	6.53	0.27
0.01	3.5350000000000	229137.20	63.65	2.65
0.1	0.4435000000000	1826381.06	507.33	21.14
1	0.1343500000000	6029028.66	1674.73	69.78
10	0.1034350000000	7831004.98	2175.28	90.64
100	0.1003435000000	8072271.75	2242.30	93.43
1000	0.1000343500000	8097218.61	2249.23	93.72

The tag's body is manufactured from plastic or polymer. The microcircuit that records the temperature changes is contacting the tag`s body by means of dielectric layer placed between the microcircuit and tag`s body providing maximum accuracy of temperature changes.

Tag's clock calibration is performed via the tag's data interface. If required the data in the tag can be encrypted by either symmetric or asymmetric encryption scheme.

In order to increase battery life (particularly in case of the wireless connection), the tag can be programmed to turn on (and start recording and listening for wireless commands) after a certain period of time, as opposed to immediately after being manufactured. Alternatively, the tag can turn on when it detects a specific event (e.g., using a magnetic switch/sensor).

The tag itself can be a system, distributed in space. For example, sensors can be located in different parts of the cargo container and the electronic components can be located in one place, connected (wired or wirelessly) to the sensors, decreasing the overall cost of the system.

Electronic components with memory can be located in a container lock, thus giving an opportunity to log not only the environmental conditions, but also the physical access to the container. Low-power wireless solutions such as Bluetooth 4.0 can significantly increase the usability of the system. The tag data records can be accessed not only from a specialized reader, but also from a smart-phone, a tablet PCs, etc. This simplifies the cargo check procedures and eliminates the need of using specialized reader – all functionality of the reader can be implemented in a smart-phone/tablet PC application.

Tags can have one sticky surface covered by a non-sticky film to prevent it from being covered with dirt or dust, so the tag can be easily attached to any surface. The tags (housing) can be made of a semi-flexible printed circuit board (PCB) to be fixed on non-flat surfaces. The tag itself can be made flexible, e.g., using flexible mounting surfaces, such as mylar, as housing, to make it suitable for complex-shaped shipping and mail envelopes.

After the cargo is delivered to the warehouse, the tags can be used in sorting and accounting processes using additional shipment data stored in the tag's memory. Inserting a beeper inside the tag can help in finding the items inside the non-automated warehouses.

Figure 11 illustrates a tag life time flow chart. The tag is manufactured, activated and placed inside package (goods). The tag can be activated wirelessly (using tag wireless interface) after it has been placed inside the package. During transporting of the package the tag data can be read via the tag wireless interface. After transportation the tag is extracted from the package and the tag data is read by the tag reader. If needed, the data can be compressed for storage and/or transmittal.

The tag can be implemented as a PCB module that can be mounted (using soldering or sockets) with other PCBs. Also, tag readers can be implemented as stationary modules on checkpoints of logistics to perform control automatically.

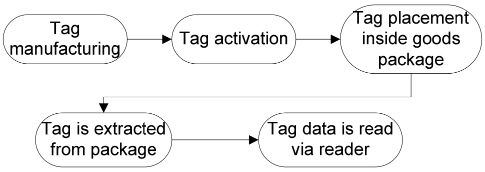

Figure 11: A life cycle of the tag.

Furthermore, the tags can have two power sources – a direct current power source, such as a battery, and one or more inductive coils to be powered wirelessly, which is useful for reading data from tags with exhausted batteries.

The tags can be synchronized with other machines, such as robots or warehouse machinery, via a wired or a wireless interface or through the reader, via wired or wireless interface, to perform goods rejection automatically. Also, the tags and/or readers can use wired or wireless interfaces to upload data to the Internet and to a remote server to perform online state checks.

3 CONCLUSIONS

The tag monitors the environmental conditions with particular sensors and logs all detected violations of the monitored conditions with timestamps into its memory. The tag reading device can communicate with the tag via a wired or wireless interface to transmit the data about conditions violations and display this information on its screen or forward it for storage.

As competing systems for monitoring environmental parameters during transportation HygroBouton (Proges-Plus company, 2014) and Hygrochron (TERMOCHRON Elin – Russia (Elin, 2014)). Table 3 presents main specifications of the above monitoring systems.

Table 3: Comparison of systems for monitoring environmental conditions during transportation.

	HygroBouton	Hygrochron	BBT
Temperature range	-20/+85°C	-20º/+85ºC	-40/+86ºC
accuracy	± 0.5°C	± 1°C	± 0.5°C
Humidity range	0-100 %	0-100 %	0-100 %
accuracy	± 5%	±1%	± 0.5%
Vibration monitoring	-	-	Not limited
accuracy	-	-	2mg
Reader	Needed	Needed	Not needed

The study is underway to improve the accuracy of registered temperature and developing conditions for providing monitoring of humidity, “lab on a chip” chemical analysis and vibration. Moreover, humidity monitoring accuracy and performance is being tested.

In order to reduce the energy consumption and increase the life-time of the tag the study will also focus on development of the software for data compression as well as its processing before transmitting the data array to the PC.

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