RobUV–Robotic Decontamination System

Kazimierz Dzierżek and Maciej Rećko
Faculty of Mechanical Engineering, Bialystok University of Technology Białystok, Poland
Email: {k.dzierzek, m.recko}@pb.edu.pl

Maciej Zajkowski and Urszula Błaszczak
Faculty of Electrical Engineering, Bialystok University of Technology Białystok, Poland
Email: {m.zajkowski, u.blaszczak}@pb.edu.pl

***Abstract*— The presented paper describes a design process of a robotic system capable of disinfecting surfaces and air by means of UV-C radiation. Two robots were designed, to cover the broadest spectrum of decontamination needs as well as complement each other's cleaning results. First, ROBUV-SUR is capable of disinfecting surfaces and can autonomously disinfect rooms and corridors with minimal human input. The second one – ROBUV-AIR – is designed to operate alongside people traversing corridors and hallways whilst cleaning air. Both of designed robotic mobile platforms use UV-C emitters adapted to fulfil the desired task. Its electronics composition and operation algorithm follow mechanical design's description. The next part of the paper considers the optimal UV-C radiation source suitable for each respected task. Our tests have shown that while commonly used UV-C radiation sources such as mercury-type fluorescent lamps are ideal for this use case, novel high power solid-state LEDs are subject to ageing, rendering them unsuitable for our project.**

***Index Terms*— mobile robot, UV-C radiation, ultraviolet, decontamination, disinfection**

I. INTRODUCTION

Widespread SARS-CoV-2 resulting in staggering COVID-19 cases has led to an increasing need for reliable, thorough yet easy to use and the least intrusive means of surface decontamination. Studies indicate that the virus can be spread via contact with a contaminated surface. Moreover, the severity of the disease depends highly on the viral load induced to the system. However, traditional means of surface cleaning is far from being safe. Apart from being highly laborious task, it utilizes chemicals that can cause irritation of skin and mucosa. Several means of alternative cleaning approaches are currently under investigation i.e., use of microbicides, pasteurization etc. The most popular alternative known for years for its effectiveness against microbial life is the use of high-power short wavelength radiation sources (UV-C emitters). Unfortunately, it is not feasible to equip every surface with a corresponding decontaminating lamp. This became the reason for our works on the development of the system that could solve this problem.

In order to cover the largest area possible to decontaminate surfaces and air in healthcare facilities by means of UV radiation, we developed an autonomous robot carrying UV-C emitters. This research is a part of the greater project aiming to improve patients' hospital experience beginning with admission registration, cleaning rooms and corridors, and humanising social experience even on closed-off wards.

Currently, we know that UV-C is a potent disinfectant wildly used as lamps in hospitals for years. Several studies have focused on quantifying its effectiveness on selected microorganisms [1,2]. Their findings show a significant reduction in the growth of various pathogens when exposed to UV-C radiation, which means that this method achieves desired results. Shortly after the spread of SARS-CoV-2, researchers tried to determine how to fight this virus. Papers focused on means of transmission, and further, it's reducing through decontaminating appeared. Their findings suggest that UV-C is able to reduce the activity of the virus or kill it entirely [3-8].

Figure 1. ROBUV-SUR

Equipped with this knowledge, we have decided to employ our expertise in robot design to reduce human factors when exposed to dangerous pathogens. We were not alone in those considerations, as scientists and entrepreneurs worldwide have prepared various solutions [9]. Robots were an obvious choice as tools to fight the pandemic [10-12]. Interestingly, in a letter to Antimicrobial Resistance and Infection Control [13], researchers have concluded that UV-C emitting robots would be beneficial and a whole system that would ensure quick, easy and safe admission, stay and discharge

Manuscript received January 14, 2022; revised April 1, 2022.

doi: 10.18178/ijmerr.11.6.405-410

from the hospital system. We also share this idea. This is why we decided to cooperate with MSWiA's hospital to develop such a system.

Ultimately, the ROBUV robotic system will consist of two robots, one of which will decontaminate the surface by direct irradiation in the absence of humans, while the other will sterilize the air and move autonomously around the hospital ward. In addition, it is planned that the robot dock also has the functionality of air sterilization and irradiation of small objects, overalls, masks to disinfect them.

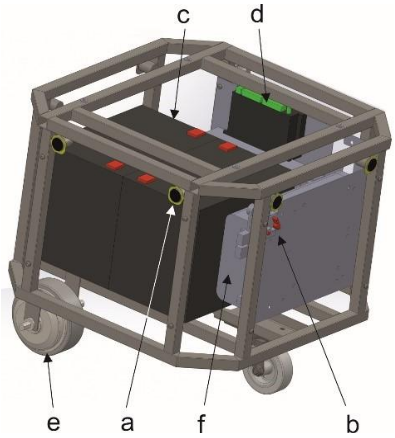

Figure 2. Internal components of a mobile platform: a – ultrasonic sensor, b – circuit breaker, c – battery, d – motor driver, e – BLDC hub wheel, f – power converter

The result of the design work is the development of the concept of two robots equipped with UV-C radiation emitters. Visually, these robots are a unified, compact design that features the necessary drive control, obstacle detection, UV-C emitter power supply, and a battery pack to ensure uninterrupted operation. The unit designed for for the surface irradiation is named ROBUV-SUR (Fig. 1) and for air sterilization ROBUV-AIR (Fig. 3). Both models are based on the same, scaled-up mobile platform (Fig. 2). The main difference is that ROBUV-SUR is equipped with extendable arms with UV-C emitters to illuminate the space under the beds in its lower part.

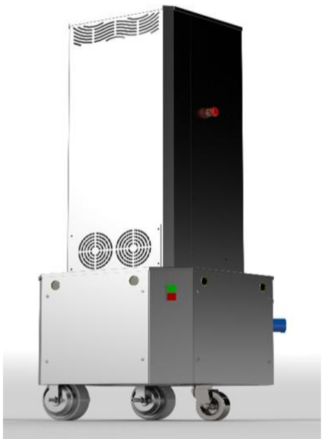

Figure 3. ROBUV-AIR

Robot visualizations were performed (Fig. 4), considering design assumptions as well as surface and workspace requirements.

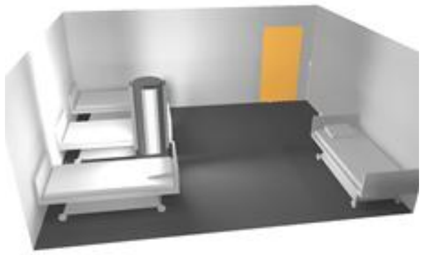

Figure 4. Visualization of robotic systems within work environments

II. Mechanical Design

Both robots share common subsystems to reduce manufacturing costs and development time. Each mobile platform is constructed on the basis of an internal frame, which is welded of stainless steel to ensure robustness. In both cases the outer shells are made of bent sheets of stainless steel. This feature originates from the need for thorough cleaning of the equipment itself. By minimizing the number of visible joints, we were able to reduce the number of nooks and crannies that would allow microorganisms' growth.

Depending on the intended application, the UV-C emitters are either on display – for the surface model or encased. In both systems, there was a need to harvest the emitters' total output by directing them onto the desired path. Basing on our experience, we decided to use highly reflective in UV range h17 14016 stainless steel sheets to form the reflectors.

In order to allow robots' autonomous movement, they are equipped with BLDC integrated hub wheels with tires made of medical-grade silicone. This solution provides reliable means of propelling the platform while respecting the high hygiene standards required in the targeted use environment. The control of the motors is achieved using controllers, one for each wheel, with embedded safety features like emergency braking and soft start/stop sub-procedures.

Developed robots are equipped with battery packs composed of two LiFePO4 cells based on the shelf batteries. Each of them has independent charging circuitry. However, their power output is combined to power the true sine wave DC/AC converter. This approached allowed usage of common parts such as ballasts and UV-C emitters, further reducing costs of manufacturing and explanation while ensuring ease of maintenance and availability of spare parts in the future.

The main difference between robots is the placement of UV-C emitters. ROBUV-AIR has air ducts in its tower that allow air movement around emitters while containing the radiation within the device. The tower of the ROBUV-SUR has exposed emitters, that allows radiation light to reach various surfaces of disinfected areas, thus fighting microbial life.

III. Electronics and Programming

A. *Electronics*

In order to ensure the autonomous movement of robots in the corridors of the hospital and correct operation and diagnosis of the system, the following components were chosen and tested:

- Intel RealSense cameras with LIDAR laser sensors generating distance field image,
- Raspberry Pi single-board microcomputers,
- modules with Multi-core Propeller microcontrollers from Parallax,
- step-down power converters for powering electronic devices,
- distance sensors,
- remote controllers,
- drive motor controllers,
- LCD display.

Aiming at assurance of independent recognition of the direction of the corridor axis or the position of the open doors and obstacles detection in its path application of the camera is necessary. In our system we used RealSense camera working with Raspberry Pi. In addition, the selected solution has an enormous advantage over traditional Lidar systems due to its lack of mechanically rotating parts. In this way we exclude the problem of proper disinfection of the joints and eliminate the possibility of usefulness of our system in the fight against dangerous pathogens due to growth of microbes on the moving elements of the robot.

In order to assure evaluation of the distance an ultrasonic distance sensor with a range of 20 cm-10 m was tested. The advantage of these sensors is their low price and simplicity of operation. The main disadvantage is the low resistance to interference, both electromagnetic and introduced in the supply voltage. It is possible to use these sensors in the designed robot, but it requires careful design of the circuit boards, their placement inside the robot and the selection of power supply devices. Laser distance sensors are smaller and more resistant to interference than ultrasonic sensors but require more complex control operation executed by the microcontroller. Distance sensors, regardless of the chosen model, should be used to protect the designed robot from collisions with objects that may appear in its path and maintain a certain distance from the walls of the corridor or hall. Usage of both kinds will double assure assumed measurement correctness.

The robots will be supplied through the batteries with a voltage of 24-28.8 V. However, our studies have revealed that inverters with an operating frequency of 120 kHz interfered with the above-mentioned ultrasonic distance sensors. The problem was solved by using drives with a higher (180 kHz) operating frequency.

The number of input/output signals needed to control the designed robot has been estimated at around 40, depending on the final selection of other controls. In this situation, a microcontroller with a large number of inputs and outputs and sufficient computing power should be used in order to control the system and be able to react to sudden events without unnecessary delays. For this purpose a Parallax Propeller 2 microcontroller (USA) was selected. It is equipped with 64 general-purpose input/outputs, although about 60 outputs remain at the user's disposal due to the communication with the programmer and non-volatile memory. This microcontroller consists of 8 CPU cores, which allow to separate tasks between them so that they do not interfere with each other, ensuring low response time even without using an interrupt system. The use of these modules allows to simplify the design of the control electronics and replace the microcontroller in case of damage quickly. The Propeller 2 has a large number of A/C and C/A converters, allowing it to be used in devices that transmit measurement data or use analogue control signals.

For the service and diagnosis, the robot as well as assessing its current condition (e.g. battery level) the LCD display is used. Due to operation by the hospital employees, to allow functions selection without using a remote control it is required to use access buttons. Also, a USB connector to communicate with PC for diagnostics or software updates is necessary.

B. The Algorithm

A simplified algorithm of operation is depicted in Fig. 5. The robot uses both remote control and autonomy algorithms as means of navigation within wardrooms in hospitals. The autonomy algorithms will also be aided by 3D scans of rooms available within the system's memory and selected based on a QR code associated with a room.

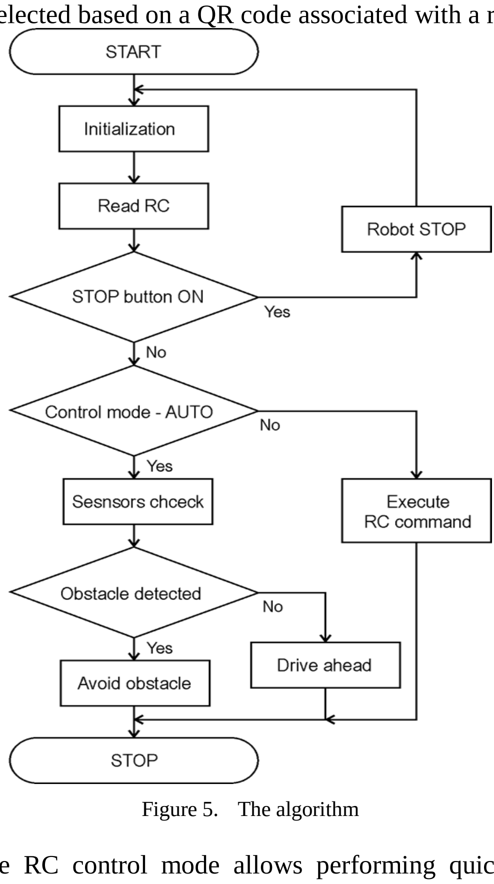

Figure 5. The algorithm

The RC control mode allows performing quick and easy disinfection of not previously surveyed rooms as well as transportation between them.

Fully automatic mode allows following preprogrammed path created using intuitive creator whilst first run in a new area. Then, using the RC controller, the operator gives instructions guiding the device along walls and areas that require more thorough irradiation exposure. Those instructions are then stored in the robot's memory for further use. When re-running this program, the robot will recreate the guided path of movement and inform the operator if any obstacles are not included in the program, asking to remove them.

Finally, the second autonomous mode will not rely on the previous scan of the area. Instead, it will keep a set distance to the wall and follow its length until no further movement in that regard is possible. Then, the robot will turn back and follow its "footsteps" if the opposite wall is not detected or change the wall to follow while moving in the opposite direction from where it started. Throughout the described operation, the robot monitors its surroundings and avoids avoidable obstacles, keeping away from staircases, barriers, and other architectural features like mezzanines. This movement will carry on until the robot is directed to stop or preselected time of disinfection was reached.

In addition, using LCD user can get information about remaining power, use advanced features like preprogramming paths, editing them, and invoking those when needed. It will also provide diagnostic information for maintenance and service needs.

IV. Choosing UV-C Emitters

The possible UV radiation emitters were considered for use in the project. As a result, the following radiation sources were selected for laboratory testing:

a) Deuterium: Long Life type 4000h L6565 with power supply C9598-2510,

(b) Mercury-type fluorescent lamps: four-prong connectors with a power output from 4W to 75W and a dedicated power supply system,

c) SSL solid-state LEDs and modules with optical power from 30mW to 140mW and maximum wavelength in the range of 265nm to 280nm, along with dedicated power supply systems.

A. Tests

Both Deuterium and Mercury based types of UV-C emitters were tested by us and their power outputs, wavelengths, and performance stay within the producer's declared values. However, due to insufficient manufacturer data provided for UV-C LEDs, laboratory tests of selected parameters of the emitters had to be done. For this purpose, measuring stands were built to study the effect of temperature on the electro-optical characteristics of diodes and their ageing.

Tested LEDs show very high spectral stability in relation to temperature and current – both the wavelength for which there is a maximum emission and the half-width is not changing with the variation of temperature.

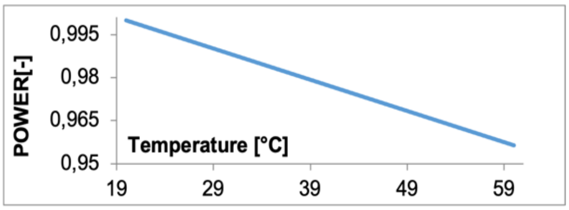

Figure 6. Relative characteristics of the influence of temperature on the power emitted by the UV-C LED emitter H565C2F33Z29-S2P3

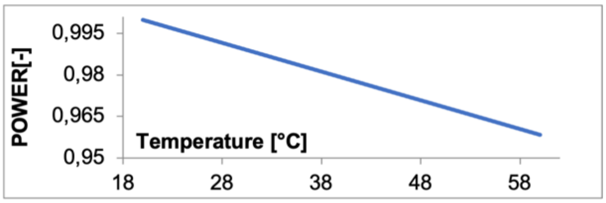

Figure 7. Relative characteristics of the influence of temperature on the power emitted by the UV-C ST-POBA20 LED emitter

The characteristics in Figs. 6 and 7 show that an increase in temperature from 20° to 60° causes an approximately 4% decrease in the amount of radiation emitted, which means that the power emitted by the source is not very sensitive to temperature changes under the condition that the heat is dissipated from the LED, however it has to be taken into account when the irradiation time is calculated for the complete disinfection.

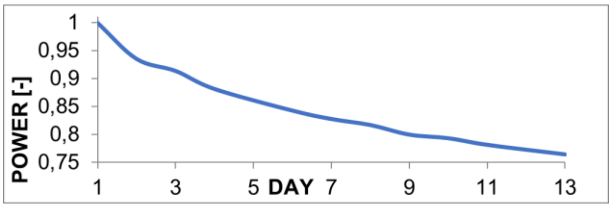

Figure 8. Relative characteristics of the effect of working time on the power emitted by the UV-C LED emitter H565C2F33Z29-S2P3

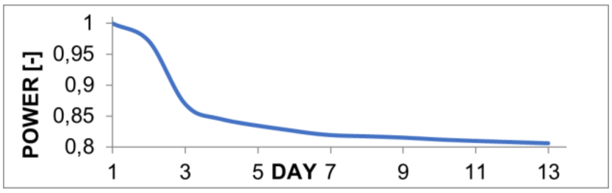

Figure 9. Relative characteristics of the effect of working time on the power emitted by the UV-C ST-POBA20 LED emitter

Figs. 8 and 9 show the characteristics of the effect of working time on the power emitted by the LEDs tested. The LEDs were tested in continuous mode, i.e. a total of about 330h. Results present a variability of available high power UV-C LED solutions. We obtained two various shapes of characteristics of decrease of the amount of radiation – in one case it was more rapid at the beginning. After the same period of time one type of emitters tended to stabilize, while in case of the second the amount of radiation was still decreasing.

B. Results

Based on the available documentation and publication reports, it was found that the sample containing the SARS-CoV-2 virus, treated with different doses of UV-C radiation from conventional radiators, partially deactivated the virus under different conditions. A dose of 5mJ/cm2 was used, which reduced SARS-CoV-2 by 99% in just 6 seconds. Based on the results of the studies, it was determined that a dose of 22 mJ/cm2 would reduce the number of viruses by 99.9999% within 25 seconds. According to the National Health Commission in China, recommendations for the distribution of irradiation intensity on the surface should be about 1.5 W/m2, at an exposure time of 30 minutes. For radiation with an effective emission value of 254 nm, the recommended energy level of 1350 J/m2 can be assumed. On this basis, further analyses on the distribution of UV-C irradiation intensity will refer to this type of energy level. However, analyses will be conducted on the choice of radiation intensity level and exposure time to ensure optimal conditions due to degeneration or damage to the irradiated surface material.

V. Conclusions

In this manuscript we present general issues of our construction of the robotic decontamination system. The system is the answer to one of the real problems of the hospitals in the pandemic circumstances. For this reason, we started cooperation with the MSWiA hospital in Bialystok under a joint R&D project. Wide consultations with the hospital employees allowed us to understand the needs of the hospital and propose the system composed of two independent disinfecting units based on the same construction. One of the units is dedicated to the continuous air disinfection, also with the presence of humans, while the second one aims at the direct irradiation of various surfaces in the hospital. We analyzed the parameters and availability of mechanical, electrical and electronic components necessary to construct such system and proved that the system can be developed on the basis of widely available elements and materials. Unfortunately, sometimes the data delivered by the manufacturers are not complete. An example of such element are high power UV-C LEDs. Although it is proved that they can be used for the disinfection [17], the procedure of their control has to include the effect of their aging as it may cause the decrease of the efficiency of decontamination. For this reason other sources of UV-C radiation should still be taken into account when construction such systems.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

KD and MR were responsible for designing a manufacturing of the robot. UV-C emitters analysis was responsibility of MZ and UB. All authors have contributed to writing presented paper. Both MR and UB have redacted and made necessary corrections to the paper. All authors have approved its final version.

Acknowledgment

The work was carried out as part of the project "PROTECT MED – development of innovative solutions to increase the safety of staff and patients of infectious and single-name hospitals", implemented as part of the The National Centre for Research and Development project "Support for single-name hospitals in the fight against the spread of SARS-CoV-2 infection and in the treatment of COVID-19".

References

[1] J. H. Yang, U. I. Wu, H.M. Tai, and W. H. Sheng, "Effectiveness of an ultraviolet-C disinfection system for reduction of healthcare-associated pathogens," *Journal of Microbiology, Immunology and Infection*, vol. 52, no. 3, pp. 487–493, June 2019.

[2] A. E. Martínez de Alba, M. B. Rubio, M. E. Morán-Diez, C. Bernabéu, R. Hermosa, and E. Monte, "Microbiological evaluation of the disinfecting potential of UV-C and UV-C plus ozone generating robots," *Microorganisms*, vol. 9, no. 1, p. 172, Jan. 2021.

[3] J. Sagripanti and C. D. Lytle, "Estimated inactivation of coronaviruses by solar radiation with special reference to COVID‐19," *Photochemistry and Photobiology*, vol. 96, no. 4, pp. 731‐737, July 2020.

[4] T. To et al., "UV, ozone, and COVID-19 transmission in Ontario, Canada using generalised linear models," *Environmental Research*, vol. 194, p. 110645, Mar. 2021.

[5] N. C. Rockey, J. B. Henderson, K. Chin, L. Raskin, and K. R. Wigginton, "Predictive modeling of virus inactivation by UV," *Environmental Science & Technology*, vol. 55, no. 5, pp. 3322–3332, Feb. 2021.

[6] R. Rendell, M. Khazova, M. Higlett, and J. O'Hagan, "Impact of High Solar UV Radiant Exposures in Spring 2020 on SARS‐CoV‐2 Viral Inactivation in the UK†," *Photochemistry and Photobiology*, vol. 97, no. 3, pp. 542‐548, Mar. 2021.

[7] W. Al-Hashemi, D. Zageer, and H. Risan, "Estimation the efficiency of sunlight UV on inactivation COVID-19 virus," *Egyptian Journal of Chemistry*, vol. 0, no. 0, Mar. 2021.

[8] S. K. Bhardwaj et al., "UVC-based photoinactivation as an efficient tool to control the transmission of coronaviruses," Science of The Total Environment, vol. 792, p. 148548, Oct. 2021.

[9] B. Saman, M. M. A. Eid, and M. M. Eid, "Recently employed engineering techniques to reduce the spread of COVID-19 (corona virus disease 2019): a review study," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 22, no. 1, p. 277, Apr. 2021.

[10] G. Z. Yang et al., "Combating COVID-19—The role of robotics in managing public health and infectious diseases," *Science Robotics*, vol. 5, no. 40, Mar. 2020.

[11] M. Tavakoli, J. Carriere, and A. Torabi, "Robotics, smart wearable technologies, and autonomous intelligent systems for healthcare during the COVID‐19 pandemic: An analysis of the state of the art AND Future Vision," *Advanced Intelligent Systems*, p. 2000071, May 2020.

[12] A. Begić, "Application of service robots for disinfection in medical institutions," *Lecture Notes in Networks and Systems*, pp. 1056–1065, 2018.

[13] M. Diab-El Schahawi et al., "Ultraviolet disinfection robots to improve hospital cleaning: Real promise or just a gimmick?" *Antimicrobial Resistance & Infection Control*, vol. 10, no. 1, Feb. 2021.

[14] J. H. Bong, "Controlling the parasite," in *Proc. International Conference on Control, Automation and Systems*, pp. 0209–0210, 2020.

[15] A. Alice and B. Bob, "Nonlinear unstable systems," *International Journal of Control, Automation, and Systems*, vol. 23, no. 4, pp. 123–145, 1989.

[16] M. Young, *The Technical Writer's Handbook*, Mill Valley, Seoul, 1989.

[17] C. Bowker et al., "Microbial UV fluence-response assessment using a novel UV-LED collimated beam system," Water Research, vol. 45, 2011, pp. 2011-2019.

Kazimierz Dzierżek PhD DSc Eng. independent researcher at Bialystok University of Technology (Poland). His postdoctoral degree was defended at Kosice University of Technology (Slovakia) in the field of automatic control and robotics, doctorate at AGH University of Science and Technology (Poland) (automatic control and robotics), and

masters and engineering degrees in the field of mechanical engineering at Bialystok University of Technology.
His scientific interests combine mechanical engineering and automatic control and robotics, as his focus is set on practical applications of such. He is a scientific advisor of a team of creators of Mars rover analogues (three-time winners of University Rover Chalenge). The expert in the National Center for Research and Development Poland

Maciej Rećko MSc. Eng. doctorate candidate at Bialystok University of Technology (Poland) in the field of mechanical engineering. He acquired both engineering and master's degree in the field of automatic control and robotics at BUT. Has successfully participated in creation of Mars rover analogue that won University Rover Challenge in 2014.
His scientific interests involve mechanical engineering as well as automatic control and robotics. He prepares a dissertation about remote control of the robotic arms using phantom device with haptic feedback

Maciej Zajkowski PhD Assoc. Prof., 2013 Bialystok University of Technology, electrical engineering Professor at Bialystok University of Technology. The area of interest: lighting technologies, RES, Smart City technologies. The expert in the National Center for Research and Development Poland. Member of PTETIS, SEP Poland.

Urszula Błaszczak obtained MSc in Optoelectronics (1999), PhD in electrical engineering (2009) at Bialystok University of Technology, Bialystok, Poland.

She has been working at the Bialystok University of Technology from 1999 at the research and didactic positions. Author of more than 50 papers and conference publications. Research interests are focused on application of LEDs, non-visual and visual effects of light and integrative lighting.
Dr. Błaszczak is a Vice President of Polish Commission on Illumination. She represents Poland in Division 6 - Photobiology and Photochemistry of International Commission on Illumination CIE. A member of Polish Society of Theoretical and Applied Electrical Engineering.