Multi-robot system for disaster area exploration

F. Burian[2], L. Zalud[1], P. Kocmanova[2], T. Jilek[2] & L. Kopecny[1]
[1]LTR s.r.o., Czech Republic
[2]CEITEC, Brno University of Technology, Czech Republic

Abstract

CASSANDRA robotic system developed at LTR s.r.o. company and Brno University of Technology is described. The system contains an operator's station controlled with one operator and a couple of robots – small and big ground robots, flying robots (quadrocopters), and mapping robot. The robots are primarily controlled by the operator with an advanced user interface with visual telepresence and augmented reality. Nevertheless, the robots include the possibility of semi-autonomous operation based on self-localisation. The user interface consists of a computer, joypad, head-mounted display with inertial head-tracker, communication device, and Cassandra software developed by our team in Microsoft .NET. Orpheus class robots are described in the text. The robots are made to be reliable and to be able to work in extreme conditions, they are tested by a series of MIL-STD military tests for environmental parameters, EMC, vibrations and shocks, contamination/decontamination, etc. Orpheus-X3 is a general US&R robot with enhanced victim search capabilities, Orpheus-HOPE is made for water contamination measurements, Orpheus-AC2 is a ruggedized version for environmental parameter measurement. Two flying drones developed completely by our team are described, as well as EnvMap mapping robot for real-time construction of spatial digital maps with texture mapping. All the robots can be controlled with the help of visual telepresence and augmented reality – that makes robot control much more intuitive, and lets the rescuer concentrate on the mission itself. The control station may be used as a self-containing wearable system. The fusion system with multispectral measurement containing tricolor cameras, thermal imagers and TOF camera is described.

Keywords: robot, user interface, telepresence, augmented reality, data fusion.

WIT Transactions on Ecology and The Environment, Vol 184, © 2014 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/FRIAR140221

1 Introduction

The reconnaissance of dangerous areas is one of the most challenging tasks for today's robotics. According to many indications, e.g. from the Robocup Rescue League community where the DCI team is involved [1, 3], it seems that nowadays the development of practical and usable reconnaissance robots is aimed at the following tasks:

- A larger number of robots controlled by one operator, in such cases as when the operator must concentrate on crucial tasks, such as victim identification, while the robots perform basic tasks, like mapping, autonomously.
- Easy and intuitive human-to-robot interface should be optimized, since the real operators will be rescuers rather than robotic specialists.
- For many kinds of reconnaissance missions it would be highly beneficial if the user interface would somehow emphasize alive people – since they are often the main objective (earthquake or floods victims, injured soldiers, criminals or terrorists).

The remote robotic reconnaissance of dangerous areas is a very complex and interdisciplinary task [7], and only well-tuned robotic systems, with good software, hardware, communication and sensory subsystem, may succeed [17]. Mobility and the ability to work reliably in hard conditions are very important. It also induces that mechanical construction and the hardware of the robots play a very important role in this complex task [13].

The authors propose a possible solution of the abovementioned problems through an advanced user interface program called CASSANDRA and show its application on several reconnaissance robots developed by our team.

Although the technical features of individual robots are supposed to differ, the robots can be divided into certain "classes" of robots that are capable of being controlled with the control system. The classes are listed below with an emphasis on their mapping and self-localization abilities.

- Bigger and more complex robots with sufficient mapping and self-localization capabilities (e.g. Orpheus).
- Small robots with limited mapping and self-localization capabilities (e.g. Perseus).
- Rotorcraft Unmanned Aerial Vehicles (UAVs) with self-localization only (e.g. Uranus).
- Mapping robots with exceptional mapping and self-localization capabilities (EnvMap).

At present, the reconnaissance robots and the operator's telepresence control system, the CASSANDRA, are completed; thus, each robot can be effectively controlled by the system. Multispectral data-fusion for colour and thermal image mixing with help of TOF camera, is finished as well. The current task consists in enabling the automatic mapping and self-localization of the robots, both outdoors and indoors, and implementation of enhanced reality mixing real telepresence data with the data from the multispectral maps.

2 Orpheus robots

Orpheus robots have been developed at Department of Control and Instrumentation (DCI) and LTR s.r.o. (spin-off Brno University of Technology) since 2003. The first version was called simply Orpheus, and our team was quite successful in Robocup Rescue 2003 world competition in Padova, Italy – we won the competition (see [1]). In 2003–2006 we improved/rebuilt the robot to the version Orpheus-X2 (see [2]). In 2006 we were asked to make a military version of the robot. The prototype was finished in 2007 and named Orpheus-AC (Army and Chemical). In 2009 we started development of second generation, based on Orpheus-A2 platform. We decided to make two basic modifications – Orpheus-AC2 for chemical and nuclear contamination measurements and Orpheus-Explorer for more general reconnaissance missions and victim search.

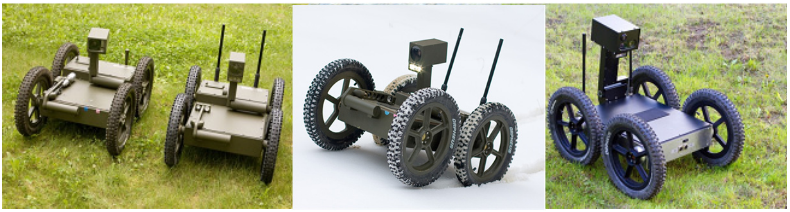

Figure 1: Orpheus robots (from left): Orpheus-AC prototype, Orpheus-AC, Orpheus-AC in snow, Orpheus-Explorer.

2.1 Orpheus-AC

Orpheus-AC (see Fig. 2) is a rugged robotic system made to reconnaissance highly dangerous areas with chemical and nuclear risks. The main mission objective is chemical and nuclear contamination measurement. The robot is equipped with beta and gamma-radiation sensors as well as LCD 3.2 chemical contamination probe. The robot is made for military purposes, so it fulfils military standards, it successfully passed 17 MIL-STD STANAG tests, e.g. environmental, vibrations, EMC, etc. The robot is equipped with two cameras – one zoom colour camera with illumination (wide and narrow light beam) with both manual and automatic parameter settings, and one rigid “rear” wide-angle camera – colour, highly sensitive. The robot has one degree of freedom manipulator with sensors, while other sensors are rigidly connected to the robot body. The robot base is rigid, has low profile with high clearance because of big wheels. The robot may be operated wirelessly or by wire. The robot is made to work in hard terrain; it is able to go across obstacles up to 20cms high; it is able to work well during the night or in bad visibility conditions (sensitive cameras, configurable illumination).

The robot itself is made to be easy to de-contaminate, the whole robot is waterproof, painted by resistive paintings and the whole construction is made to repel or at least not to keep liquids. Only several parts are marked as non-decontaminable and have to be replaced – tires, antennas and two cables.

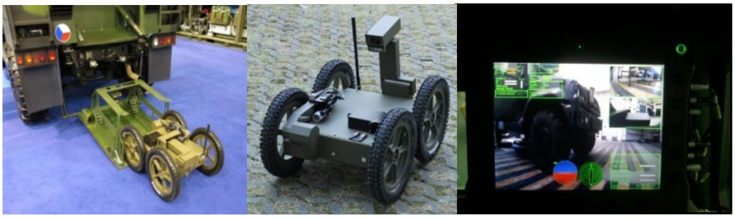

Figure 2: Orpheus-AC2 (from left) – Robot accessing the ramp to armoured vehicle, Orpheus-AC2, User interface screen inside the armoured vehicle.

decontamination process, it is newly equipped with two degrees-of-freedom sensory manipulator with beta probe, chemical sorbent tube, distance measurement and camera. Significant part of electronics is completely new, internal communication system is newly based on both CAN and Ethernet, new wireless communication modules working in licensed frequency spectrum are used. The robot is a part of CBRNE armoured vehicle and aims to primary contamination measurement in the areas with high contamination risks.

2.2 Orpheus-HOPE

Orpheus-HOPE (see Fig. 3) is a robot built on modified Orpheus-A platform and its primary mission is water contamination measurement. It is a product of research and development of our university together with Laboratory of Metalomics and nano-technology and Laboratory of Microsensors and Nanotechnology of CEITEC project.

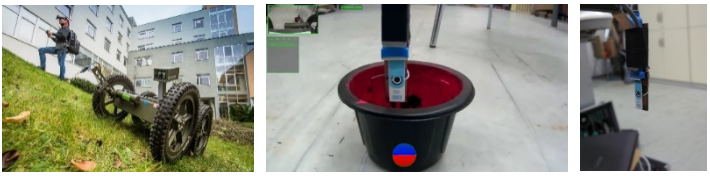

Figure 3: (From left) Orpheus-HOPE controlled by wearable operators' station, user interface screenshot during water heavy metal measurement, sensory head detail.

Its main difference to the other Orpheus robots is the sensory head on 1 DOF motorised manipulator with heavy-metal analysis probe and water dive sensor – both the sensor and probe were newly developed by our teams. The robot, in its current status is only a proof-of-concept, we are currently working on practically usable device with peristaltic pump-based system of water sampling.

2.3 Orpheus-X3

The Orpheus-X3 (see Fig. 4) is an experimental reconnaissance robot based on the Orpheus-AC2 model. It offers the same drive configuration as its predecessor, namely the four extremely precise AC motors with harmonic gears directly mechanically coupled to the wheels; this configuration makes the robot very effective in hard terrain and enables it to achieve the maximum speed of 15 km/h. The main difference consists in the chassis, which is not designed as completely waterproof but consists of a series of aluminium plates mounted on a steel frame of welded L-profiles. This modular structural concept makes the robot markedly more versatile, which is a very important aspect in a robot made primarily for research activities. Furthermore, the device is equipped with a 3DOF manipulator for the sensory head. The manipulator, again, comprises very powerful AC motors combined with extremely precise, low backlash harmonic drive gearboxes by the Spinea Company. The presence of such precise gearboxes can be substantiated by several reasons, mainly by the fact that the robot will be used not only for telepresence but also for mobile mapping and SLAM [9, 10]. As currently planned, the robot's only proximity sensor will be the TOF camera.

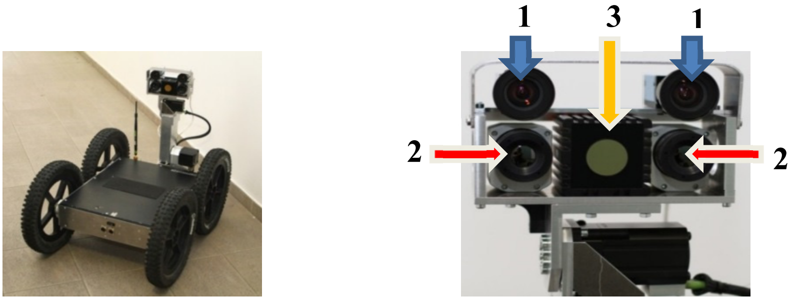

Figure 4: (From left) Orpheus-X3, multispectral sensory head. 1 – the tricolor CCD cameras, 2 – the thermal imagers, 3 – the TOF camera.

2.3.1 Multispectral data-fusion

The aim of the data fusion is to facilitate remote reconnaissance of previously unknown areas under a wide variety of visibility conditions, including fog, smoke, complete darkness, or high illumination dynamics with point light sources. It also visually emphasizes alive people (usually victims).

It represents a technique for the alignment of visual spectrum data and thermal imager data, utilizing the information provided by a TOF camera. The TOF camera measures the distance of an object, while corresponding pixels are found on the applied color camera and thermal imager. Each of the sensors has to be calibrated for geometrical errors; mutual position and orientation are found and used to secure the corresponding calibrations [6].

The sensory head is shown in Fig. 4 right. It contains:

- Two tricolor CCD cameras (see 1 in Fig. 4). The Imaging Source DFK23G445 with 1280x960 pixels resolution, max refresh rate 30Hz, and GiGe Ethernet protocol. Computar 5mm 1:1.4 lens is used.

- Two thermal Imagers (see 2 in Fig. 4). MicroEpsilon TIM 450 with a wide lens, 382x288 pixels resolution, temperature resolution of 0.08K.
- One TOF camera (see 3 in Fig. 4). A Mesa Imaging SR4000 with the range of 10m, 176x144 pixels resolution. The field of view is 56°(h) x 69°(v).

The scheme of the presented system is indicated in Fig. 5, right.

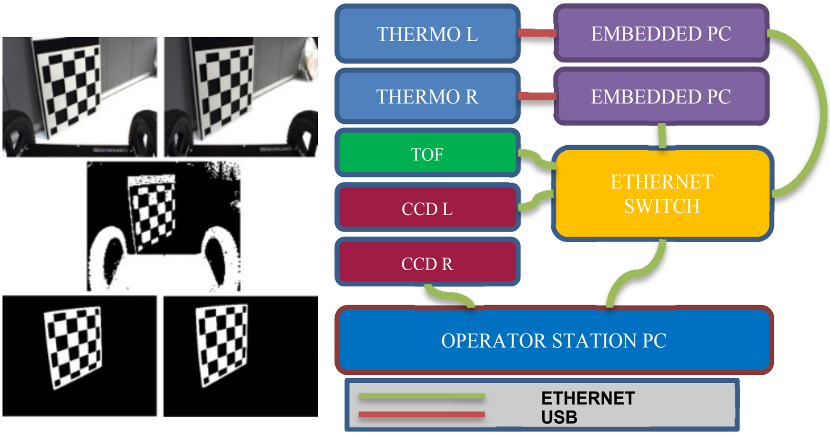

Figure 5: Calibration pattern for TOF camera, CCD camera and thermal imager (left), scheme of multispectral sensory head connections [4] (right).

The technique was already studied by our team in the past (see [14]), but as the sensory prices decreased rapidly and TOF cameras further developed, the method may be improved to reach a significantly more advanced stage.

Image transformations are applied for data fusion. The range measurements of the TOF camera can be displayed into images of CCD cameras and thermal imagers using spatial coordinates. The procedure is outlined in the diagram on Fig. 6. The input data include the range measurement, the image coordinates of all sensors, and the results of the previous calibration.

The spatial coordinates X, Y, Z are computed from Eqs (1) and (2), where d is the measured distance, x_c, y_c are the calibrated TOF image coordinates, and f is the focal length of the TOF camera. The homogeneous transformation is determined by Eq. (4), where $R_{[3\times3]}$ is the rotational matrix, $t_{[3\times1]}$ is the translation vector, and X', Y', Z' are the spatial coordinates of the second sensor. The image coordinates of the TOF camera in the next frame x_c', y_c' are computed according to perspective projection (see Eq. (4)), where f' is the focal length of the second sensor.

$$Z = d\cos\left(\arctan\left(\frac{y_c}{\sqrt{f^2 + x_c^{\,2}}}\right)\right)\cos\left(\arctan\left(\frac{x_c}{f}\right)\right) \qquad (1)$$

$$X = \frac{Zx_c}{f}, Y = \frac{Zy_c}{f} \tag{2}$$

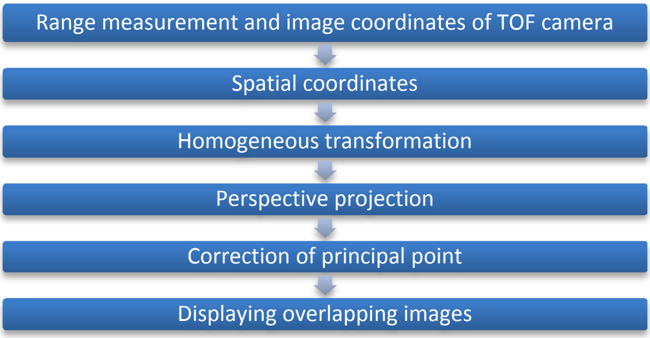

Figure 6: Image transformation scheme.

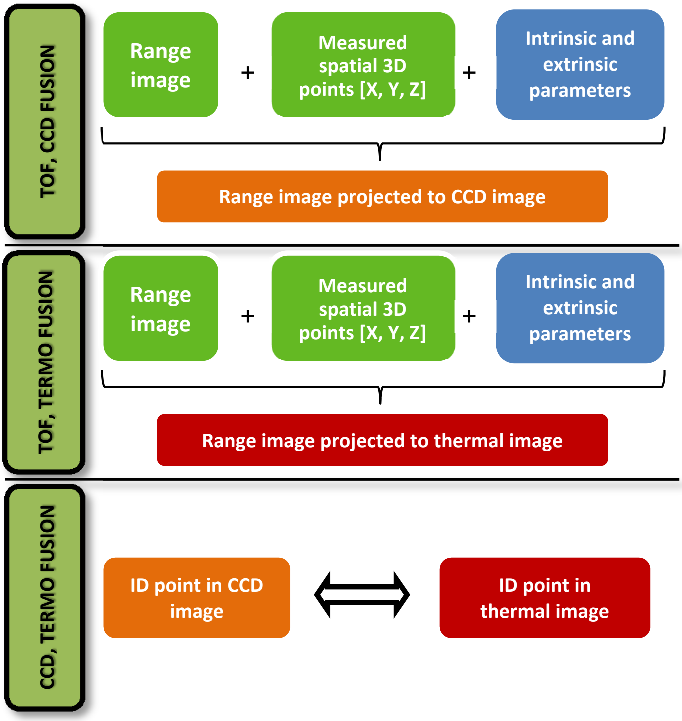

Figure 7: Scheme of data fusion: up – TOF and CCD data fusion; centre – TOF and thermal data fusion; down – CCD and thermal data fusion.

$$\begin{bmatrix} X' \\ Y' \\ Z' \\ 1 \end{bmatrix} = \begin{bmatrix} R & t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \tag{3}$$

$$x_c' = \frac{f'X'}{Z'}, y_c' = \frac{f'Y'}{Z'} \tag{4}$$

According to the identical (ID) points of the TOF camera transformed into the frames of the CCD camera and the thermal imager, the thermal image can be displayed into the CCD image and vice versa.

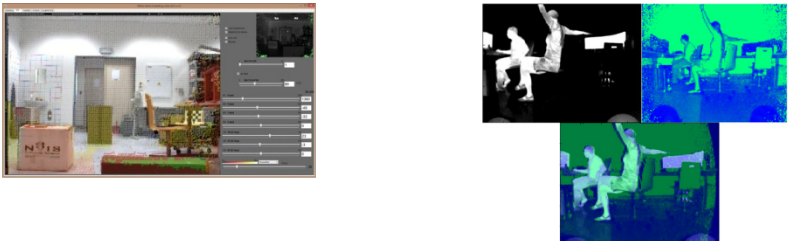

Figure 8: (Left) complete fusion for one eye; (right) top right: the range image; bottom: fusion of the range and thermal images by the described algorithm.

This is performed for two stereo pairs of cameras, and thus the resulting image may be presented to a head-mounted display with a stereovision support [16]; the operator therefore receives a very good spatial representation of the environment under any visibility conditions.

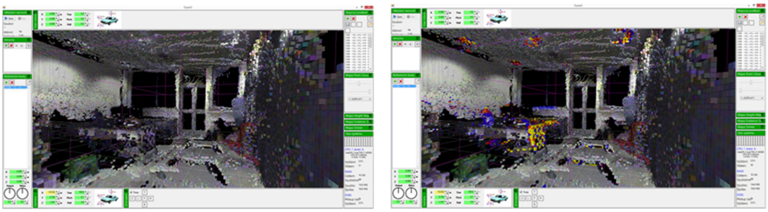

Figure 9: Data-fusion evidence grid with colour only (left) with thermal imaging (right).

It has to be pointed out that the sensors on the sensory head are not used only for this technique; simultaneously, we are also developing a SLAM technique and similar texture-mapping algorithms [11] with robot evidence grids and octree [15]. Both of these maps contain color information and thermal information [12], so e.g.

alive humans can be easily emphasized in the image – see Fig. 8. The octree map has the advantage of great loseless data-compression (up to 1:512 for the scene on Fig. 9 and resolution 1.28 cm), while the evidence grids are easy-to-modify. Currently we are able to combine both of them in one image.

3 EnvMap mapping robot

The present status of the robot being developed under the name EnvMap is shown in Fig. 10. The final design of the robot is not expected to be similar to the prototype, because the currently used drive configuration is unsuitable for hard terrain operation.

Figure 10: EnvMap robot indoors (left) and outdoors (right).

Precise digital autonomous mapping of a previously unknown environment [5] forms a crucial part of the entire robotic reconnaissance system. A typical activity requiring a faithful map of the environment is victim rescue planning, where the rescuers need to recognize the exact position of the victim, know the dimensions of the passages, and plan the rescuer passage through the area. Maps built by the robot from the surrounding of our building are on Fig. 11.

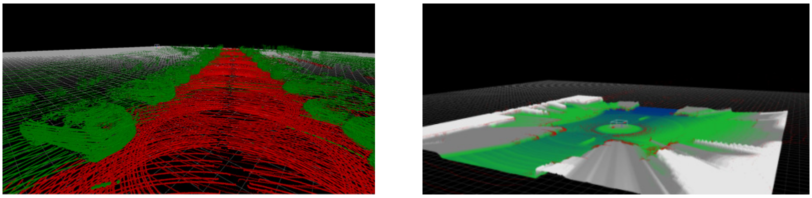

Figure 11: Spatial robot evidence grid (left) and height map (right) scanned by EnvMap robot.

4 Other robots

A couple of other robots were developed by our team as a part of CASSANDRA system. Uranus is our own multicopter [19] system. It currently contains two quadrocopters – Uranus-ALU with 350 g payload capacity, and Uranus-CARB with approx. 1500 g payload capacity (see Fig. 12).

Scorpio is an indoor robot based on Dr. Robot drive system similar to iRobot Packbot. The robot is intended for indoor operation, it is able to climb up-stairs. Our team only developed the electronics and camera manipulator. Perseus is one of our small robots capable of operation in hard terrain (see Fig. 12).

Figure 12: From left – Uranus-ALU quadrocopter, Uranus-CARB quadrocopter prototype, Scorpio indoor robot, Perseus mini-robot.

5 CASSANDRA software

All the mentioned robots may be controlled by CASSANDRA software, developed by our team. It is basically a universal user-interface program developed in Microsoft .NET 4.5, WPF. It has many displaying capabilities (see Fig. 13). The most important central part is filled with main camera image, while the corners can be covered by configurable virtual head-up displays containing video from other robot cameras or video from other active robots, as well as, other data from robot sensors or depicting system status. The system can work with variety of head mounted displays equipped with head movement sensors.

Figure 13: CASSANDRA software screenshot with description.

One of the main advantages of the whole CASSANDRA system is, that since all of the parts (i.e. all the robots, software, communication protocols) are developed by our team, it is possible to control all of the robots by one operator's station equipped with CASSANDRA software (see Fig. 14). So the operator has the possibility easily switch among the robots and select the most appropriate one for the task.

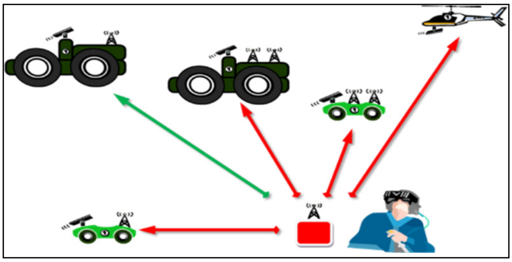

Figure 14: CASSANDRA system scheme.

6 Conclusion

The presented CASSANDRA system represents work-in-progress, rather than completely finished system. The telepresence part of the system is considered finished, currently the team works on integration of semi-autonomous and autonomous functions, like self-localisation and autonomous real-time map building. Several parts of the system are currently practically usable, e.g. Orpheus-AC2 robot, that is in active military service in the Czech Army.

Acknowledgements

This work was supported by CEITEC – the Central European Institute of Technology (CZ.1.05/1.1.00/02.0068) utilizing the European Regional Development Fund.

This work was also supported by VG 2012 2015 096 grant named Cooperative Robotic Exploration of Dangerous Areas by the Ministry of Interior, Czech Republic, program BV II/2-VS.

References

[1] Zalud, L., (2004). Rescue Robot League – 1st Place Award Winner. In: RoboCup 2003: Robot Soccer World Cup VII, Springer, Germany, ISBN 3-540-22443-2.

[2] Zalud, L., (2001). Universal Autonomous and Telepresence Mobile Robot Navigation. In: 32nd International Symposium on Robotics – ISR 2001, pp. 1010-1015, Seoul, Korea.

[3] L. Zalud, “Integration of 3D Proximity Scanner to Orpheus Robotic System”, in 16th IFAC World Congress. Prague, Czech Republic: 2005, pp. 1209-1215.

[4] Kocmanova, P., Zalud, L., Spatial Calibration of TOF Camera, Thermal Imager and CCD Camera. In Mendel 2013: 19th International Conference on Soft Computing. Brno: Brno University of Technology, 2013, pp. 343-348. ISBN 978-80-214-4755-4.

[5] Hartley, R., Zisserman, A., Multiple View Geometry in Computer Vision. Cambridge, Cambridge University Press, 2003, ISBN 05-215-4051-8.

[6] Zhang, Z., Flexible camera calibration by viewing a plane from unknown orientations, In Computer vision, Vol. 1, 1999, pp. 666-673.

[7] Lundberg, C., and Christensen, H. I. Assessment of man-portable robots for law enforcement agencies. In PerMis (Gaithersburg, MD, Aug 2007), R. Madhavan and E. Messina, Eds., ACM/IEEE.

[8] Leonard, J.J., Durrant-Whyte, H.F. (1991). “Simultaneous map building and localization for an autonomous mobile robot”. Intelligent Robots and Systems’ 91. ‘Intelligence for Mechanical Systems, Proceedings IROS’91. IEEE/RSJ International Workshop on: 1442–1447. doi:10.1109 /IROS.1991.174711. Retrieved 2008-04-08.

[9] Karlsson, N., Di Bernardo, E., Ostrowski, J, Goncalves, L., Pirjanian, P., Munich, M. (2005). “The vSLAM Algorithm for Robust Localization and Mapping”. Int. Conf. on Robotics and Automation (ICRA).

[10] Ju, X., Nebel, J.-C., Siebert, J. P., 3D Thermography Imaging Standardization Technique for Inflammation Diagnosis. In Proceedings of the SPIE, Vol. 5640, 2005, pp. 266-273.

[11] Prakash, S., Pei Yean Lee, Caelli, T., 3D Mapping of Surface Temperature Using Thermal Stereo, In Control, Automation, Robotics and Vision, 2006, pp. 1-4.

[12] Tournas, E.-Tsakiri, M., Distance Error Estimation for Range Imaging Sensors. In: Proceedings of the ISPRS Commission V Mid-Term Symposium “Close Range Image Measurement Techniques”, Vol. XXXVIII, 2010, Part 5, pp. 581-585. Newcastle upon Tyne, United Kingdom, 21.-24. 6. 2010.

[13] Wise, E., (1999). Applied Robotics, Prompt Publications, USA, ISBN: 0-7906-1184-8.

[14] Henning Eberhardt, Vesa Klumpp, Uwe D. Hanebeck, Density Trees for Efficient Nonlinear State Estimation, Proceedings of the 13th International Conference on Information Fusion, Edinburgh, United Kingdom, July, 2010.

[15] Posted on (19 December 2011). “Understanding Requirements for High-Quality 3D Video: A Test in Stereo Perception”. 3droundabout.com. Retrieved 29 March 2012.

[16] Robin Ritz, Markus Hehn, Sergei Lupashin, and Raffaello D’Andrea, “Quadrocopter Performance Benchmarking Using Optimal Control”, IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 5179-5186, 2011.

[17] “CBRN Defence Market Forecast 2014-2024”. http://www.visiongain.com/Report/1206/CBRN-Defence-Market- Forecast -2014-2024 London, U.K. 14 February 2014. Retrieved 24 March 2014.

[18] Zalud, L., Burian, F., Kopecny, L., Kocmanova, P. (2013). Remote Robotic Exploration of Contaminated and Dangerous Areas, International Conference on Military Technologies, pp 525-532, Brno, Czech Republic, ISBN 978-80-7231-917-6.