VILNIUS UNIVERSITY

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HYBRID OBJECT TRACKING METHOD FOR AUGMENTED REALITY SYSTEMS USING THE KALMAN FILTER

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VILNIAUS UNIVERSITETAS

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HIBRIDINIS OBJEKTŲ SEKIMO METODAS PAPILDYTOS REALYBĖS SISTEMOSE NAUDOJANT KALMANO FILTRĄ

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Introduction

Scope and Relevance of the Research

An augmented reality technology has evolved from the so-called virtual reality field, but differently from the augmented reality, a virtual reality user cannot interact with the real environment. The main augmented reality application fields are medicine, education, manufacturing, entertainment, marketing, etc. The augmented reality allows us to see the real world and place virtual objects or other information on the top of it. In this way, objects are not replaced, but integrated into the reality. Tracking tasks are solved mostly using computer vision methods that acquire and process complex information from the real environment. This provides relatively reliable information on how and where the virtual content should be displayed to users. Efficient accomplishment of the object recognition and tracking process is the main task that must be solved in the augmented reality field to display a virtual content, using a camera view of the device with respect to the tracking object. Currently the augmented reality is used for mobile devices, therefore, the solution is required for optimal object recognition, tracking, and virtual content representation tasks. At the moment, inertial sensor systems are mostly used to estimate the orientation of objects, for instance, mobile devices, therefore it seems promising in the field of augmented reality. The main augmented reality research directions are related to the following aspects:

a) Hardware and software to display the graphical virtual content in the real world view.

b) Tracking methods that allow us to add properly a virtual content in the real world view.

c) Tracking method calibration and registration tools for accurate real and virtual view synchronization for a user.

d) Display hardware to connect virtual and real world views.

e) Computer hardware for augmented reality algorithm processing.

f) Interaction methods which allows users to manipulate with a virtual content in the augmented reality environment.

Originally a full augmented reality application development consists of hardware, software, and methods from a)-f) integration. Mostly the research work analyzes tracking methods as it is a fundamental task, used in the augmented reality technology, and still has many unsolved problems to estimate the object position and orientation in a space at the same time. Other research topics are related to interaction methods, based on which interaction with a digital content takes place.

Relevance of the Research Problem

Augmented reality is a widely used visualization method in various application fields, usually in tracking artificial objects, for instance, square markers that let users to add a 2D/3D virtual content into a proper position and orientation of the real world. The main issues using markers are occlusions of users or objects in the environment. These occlusions usually cause disappearance of the virtual content, therefore they have a negative impact on the usability of applications. Some computer vision methods allow us to solve partial occlusion problems while viewing the virtual content in the augmented reality, however, it is necessary to estimate the image processing speed and suitability, since these tasks must be executed in real-time. The marker-based tracking method decreases computing requirements, but it is limited due to the marker size, interruptible tracking, and the tracking continuity only when the marker is in the field of view. The main problem of the computer vision method in real-time systems is environmental complexity and tracking object motion. For example, the tracked object can separate or merge because of partial occlusions or image noise, object view can change because of the illumination level and features of the objects from a further distance are not reliably reconstructed, therefore, object orientation and position are computed inefficiently. Fast or irregular camera motion can cause image tracking failures and instabilities. Some of the drawbacks can be eliminated, using inertial sensors for fast device camera orientation changes and successful object orientation estimation in the camera view. However, separate sensor information is not accurate or reliable as it is impacted by noise, drift, and magnetic interference, therefore, there is a need to develop an effective pose estimation model.

Object of the Research

The main object of research is object tracking methods in augmented reality systems, which allow us to estimate object orientation and position in a real space, based on computer vision and sensor fusion.

Aim of the Research

The aim to propose a hybrid object tracking method, using the Kalman filter in the augmented reality field, based on computer vision and sensor fusion methods in order to improve the object orientation and position tracking accuracy in a real space.

Objectives of the Research

To achieve the research aim this objectives were determined:

1. To perform object tracking research based on computer vision and sensor data fusion methods to propose application recommendations in the field of augmented reality.
2. To analyze inertial sensors application possibilities and carry out the experiments on sensor orientation data fusion methods in order to apply object orientation tracking information not only augmented reality systems, but also in constructing an interaction device to control the digital content.
3. To propose a hybrid object tracking method, using the Kalman filter for the augmented reality field, that has supplementary properties for estimating orientation and position that ensures improved object tracking solution with respect to accuracy and reliability, as compared with the use of non-hybrid methods.
4. To compare the research results of the hybrid object tracking method using the Kalman filter with the basic orientation and position data and to apply this solution in the field of the augmented reality on the internet of things, in this way ensuring a continued virtual content representation in real-time while camera is in fast motion or occlusions in the environment.

Research Methodology

In the analysis of scientific researches of object position and orientation tracking, the information search, systematization, analysis, comparative analysis, and generalization methods were used. Based on the accomplished theoretical and empirical researches, a prototype of interaction device has been developed and a hybrid object tracking method using Kalman filter was proposed. Based on the experimental research method, the analysis of digital signal processing and statistical research results was made, and to estimate the acquired results comparative and generalization methods were used.

Scientific novelty and importance

While preparing the thesis, the following new scientific results have been obtained:

1. Most of the analyzed object tracking method researches are more of a descriptive manner or analyzes only partial problem: a) estimation of position and orientation using only computer vision methods; b) estimation of only position or only orientation using sensor data fusion methods. There are no systematic researches that would allow us to reduce computer vision drawbacks, when object tracking is lost because of the changing external properties after image transformations, occlusions or other environment conditions, using additional object tracking methods, for instance, sensor data fusion, however, exclusively in this dissertation such research is provided.
2. A hybrid object tracking method, using the Kalman filter, was proposed that distinguishes by supplementary properties in respect of object position and orientation, where separately used object tracking method (computer vision or sensor fusion) drawbacks are eliminated such as noise, drift and tracking instabilities. These improved aspects are critical because of the issues in computer vision and sensor data fusion methods. Hybrid object tracking method results experimentally evaluated and compared with imitated computer vision and sensor data fusion method, show an increased tracking accuracy. The orientation error, estimated by the hybrid object tracking method, using the Kalman filter is $RMSPE_{KF}^{o} = 0{,}24\%$, in the case of only sensor data fusion – $RMSPE_{SF}^{o} = 0{,}30\%$ and in the case of only computer vision method– $RMSPE_{CV}^{o} = 0{,}30\%$. The estimated position error in the case of hybrid object tracking by the Kalman filter is – $RMSPE_{KF}^{p} = 0{,}96\%$, in the case of only sensor data fusion is $RMSPE_{SF}^{p} = 13{,}06\%$, and in the case of only computer vision method is $RMSPE_{CV}^{p} = 19{,}75\%$.
3. The accomplished hybrid object tracking method using the Kalman filter research is universal as it can be applied not only in the augmented reality systems, but also it is demonstrated that separate part of sensor data fusion can be used developing interaction device that characterizes with new ways of use.

Practical Importance of the Research Results

1. The proposed hybrid tracking method, using the Kalman filter is important in many practical application fields, but in this research it is applied in the augmented reality. The proposed method ensures reliable object orientation and position estimations, which is an important aspect of usability in the augmented reality. In such a way, a virtual content in the real-world context is ensured with uninterruptable interaction even in the presence of disturbances in the environment that occur due to rapid camera movements by a user or occlusions.
2. Depending on the available information, acquired from computer vision or sensor data fusion estimates, different approaches to orientation and position estimates are proposed incorporating new innovation conditions in the Kalman filter. The proposed hybrid object tracking method using the Kalman filter improves the object tracking reliability and eliminates delay in the computer vision case, while acquiring orientation-position estimates.

3. A mobile program of the augmented reality application has been developed for the internet of things, where the hybrid object tracking method using the Kalman filter was applied. The solution is applicable to mobile devices that have se accelerometer, gyroscope and magnetometer sensors and, by default, camera.

4. A part of the accomplished research was used in the *Erasmus IP* project "Virtual bridge construction modelling and demonstration in the augmented reality environment". International project participants are Klaipeda State University of Applied Sciences of Lithuania (Host), Leeds Metropolitan University of the United Kingdom and Varna Free University of Bulgaria, 2014.

5. The results were used in *Agency for Science, Innovation, and Technology* (*MITA*) project „Inovatyvaus verslo kūrimo skatinimas (INOVEKS)", 2014-2015, by submitting a patent application, based on the doctoral dissertation, acquired by the sensor's data fusion research results. The applicator is Edgaras Artemčiukas. Invention title is Spherical Form Interaction Device. The patent application No. is 2015 063. The application date: 2015-07-24. State: revisioned. Implementation can be viewed: *https://www.ourtechart.com/augmented-reality/demo/spherical-form-interaction-device/*.

Defended Propositions

1. In order to ensure accurate object tracking in image view and continuously display a virtual content in the augmented reality environment it is purposeful to use not only computer vision based, but also sensor data fusion methods, when sensors are attached to camera.

2. The proposed hybrid object tracking method using the Kalman filter, allow us to avoid drawbacks of non-hybrid computer vision or sensor data fusion tracking methods interruptions that might appear because of different object transformations in image, external environment condition, sensors measurements, which are attached to camera, noise, drift and other disturbances.

3. The provided hybrid object tracking method, using the Kalman filter, ensures reliable tracking object position and orientation estimates used in real conditions, while rapidly moving a camera, the tracked object is covered by occlusions, the pose in a space can be determined not only using computer vision, but also incorporating the sensor data fusion method.

LIST OF PUBLICATIONS BY THE AUTHOR ON THE SUBJECT OF DISSERTATION

Scientific Publications in the ISI Journals:

1. Artemciukas, E., Plestys, R., Andziulis, A., Gerasimov, K., Zulkas, E., Pasviestis, L., Krauze, A. (2012). Real-time Control System for Various Applications using Sensor Fusion Algorithm. *Elektronika ir elektrotechnika*, Vol. 18, No. 10, p. 61–64, ISSN 1392-1215, DOI: 10.5755/j01.eee.18.10.3064.
2. Artemciukas, E., Sakalauskas, L., Zulkas, E. (2016). Kalman Filter for Hybrid Tracking Method in Augmented Reality. *Elektronika ir elektrotechnika*, Vol. 22, No. 6, p. 73–79, ISSN: 1392-1215, DOI: 10.5755/j01.eie.22.6.17228

Scientific Publications in the ISI Proceedings:

1. Lukosiunas, E., Bulbenkiene, V., Andziulis, A., Artemciukas, E. (2011). An ultrasonic tracking method for augmented reality. *Proceedings of the 17th International Conference on Information and Software Technologies*, Kaunas, Lithuania, p. 170–173.

2. Zulkas, E., Artemciukas, E., Dzemydiene, D., Guseinoviene, E. (2015). Energy consumption prediction methods for embedded systems. *Tenth International Conference on Ecological Vehicles and Renewable Energies (EVER)*, Monte Carlo, p. 1–5, ISBN 978-1-4673-6784-4, DOI: 10.1109/EVER.2015.7112932.

Scientific Publications in Other Peer Reviewed Journals:

1. Artemčiukas, E., Sakalauskas, L. (2014). Vaizdo apdorojimo metodų tyrimas ir taikymas papildytos realybės sistemose. *Jaunųjų mokslininkų darbai*. Nr. 1 (41), p. 91–98, ISSN 1648-8776.
2. Artemčiukas, E., Sakalaukas, L. (2014). Jutiklių orientacijos duomenų integracija papildytos realybės technologijoje. *Mokslas – Lietuvos ateitis. Elektronika ir elektrotechnika*, Vilnius: Technika, Nr. 6 (2), p. 172–177, ISSN 2029-2341 (print) / ISSN 2029-2252 (online).
3. Artemčiukas, E., Sakalauskas, L. (2014). Leap Motion valdiklio taikymas papildytos realybės technologijoje. *Technologijos mokslo darbai Vakarų Lietuvoje IX*, Nr. 9, p. 10–15, ISSN 1822-4652.

International Conferences:

1. Artemciukas, E. Real-time Control System for Various Applications using Sensor Fusion Algorithm (2012). *The 16th International Conference ELECTRONICS 2012*, Palanga, Lithuania, 18th-20th June.
2. Artemciukas, E. Kalman Filter for Hybrid Tracking Method in Augmented Reality (2016). *The 20th International Conference ELECTRONICS 2016*, Palanga, Lithuania, 13th-15th June.

National Conferences:

1. Artemčiukas, E. (2013). Computer vision methods research and application in augmented reality systems. *5-oji Lietuvos jaunųjų mokslininkų konferencija „Operacijų tyrimas ir taikymai“*, Šiaulių universitetas, 19th September.
2. Artemčiukas, E. (2014). Leap Motion valdiklio taikymas papildytos realybės technologijoje. *IX-oji mokslinė konferencija „Jūros mokslai ir technologijos*, Klaipėdos universitetas, 17th April.
3. Artemčiukas, E. (2015). 3D virtualaus turinio manipuliavimas papildytos realybės technologijoje. *Penktoji jaunųjų mokslininkų konferencija: „Tarpdalykiniai tyrimai fiziniuose ir technologijos moksluose“*, Lietuvos mokslų akademija, 10th February.

General Structure of Doctoral Dissertation

Dissertation consists of introduction, 3 chapters, general conclusions, list of literature, list of author publications related to this work and list of attachments. Dissertation amount: 107 pages, 109 formulas, 46 figures, 3 tables and list of literature that contains 118 references.

In the introduction, the scope and relevance of the research, its problematic area, object, aim, objectives, research methodology, scientific novelty and importance, practical importance, defended statements and the list of publications and attended conferences are provided.

In the 1st chapter, the computer vision research was accomplished, in order to determine a suitability in developing the augmented reality systems. Some widely used modern feature extraction and matching methods were analyzed which allow us to solve partial occlusion problems and properly display a virtual content in the augmented reality. Robustness comparisons were made according to repeatability criteria, using various types of image transformation sets by verifying specific image pairs. The performance of relative computer vision feature extraction and matching methods was estimated with respect to speed and suitability for the augmented reality systems.

In the 2nd chapter, the research of sensor orientation data fusion and integration in the augmented reality was accomplished. The gradient descent method is presented and applied to microelectromechanical sensor data to accurately estimate camera orientation. It is aimed to eliminate separate sensor disadvantages and improve camera orientation tracking accuracy, reliability, and a virtual content representation in the augmented reality, without using any computer vision feature extraction and matching methods. The proposed solution was applied not only from the tracking perspective, but also in the development of interaction device. A detailed Kalman filter analysis and practical application of the acquired orientation data, based on the quaternion representation, are also presented.

In the 3rd chapter, a hybrid object tracking method is proposed in the augmented reality systems, using the Kalman filter. In the research, experiments were done with imitated object position and orientation data for the case of computer vision and sensor data fusion. The results are compared and improved aspects of the proposed methods are provided in respect of object tracking. The hybrid object tracking method, using the Kalman filter is applied to mobile devices in the augmented reality internet of things application field.

List of attachments with the content is provided within the *CD* storage media and *Google Drive*: https://drive.google.com/drive/folders/0BygvzTqnzm_wUjhaekJiNTc2bnc

A Short Description About the Author

Edgaras Artemčiukas was born on the 7th of December in 1987. In 2010, he graduated from Klaipeda University Faculty of Marine Engineering and acquired a Bachelor's degree in *Informatics Engineering*. In 2012, he gained a Master's degree in *Technical Information Systems Engineering* from the same Klaipeda University. From 2012 to 2017, he was a PhD student at Vilnius University, Institute of Mathematics and Informatics (Physical Sciences, Informatics). Since 2011, he works as a lecturer at the Klaipeda State University of Applied Sciences, Technology faculty, Department of Electrical and Mechanical Engineering. Since 2014 he has his own business in the field of IT.

Hybrid Object Tracking Method using the Kalman Filter in an Augmented Reality System

The augmented reality started to emerge as a promising visualization method that tracks real objects and adds a virtual content to the real world context using a camera view. Many the augmented reality solutions are based on computer vision methods to identify and track objects. Problems that must be solved are image transformations, chaotic environment, lighting condition, and occlusions by user' or objects in the environment, which causes a virtual content to disappear. This fact has a negative impact on augmented reality usability, therefore, object recognition and tracking in real-time becomes a difficult and sometimes an impossible task. In this research, acquisition of orientation-position information, using computer vision and sensor fusion methods, is analyzed. Experiments are done with predefined assumptions and simulated orientation-position information. Conditions for optimal orientation-position estimates are introduced. The research results are compared and supplementary properties are presented by the proposed hybrid tracking method, using the Kalman filter.

Most of the research work in the augmented reality (AR) field investigates problems that are related to tracking and interaction methods. Using tracking methods, a virtual content can be represented in an appropriate orientation and position, while changing the user's perspective, and interaction methods allow users to manipulate the virtual content. Nowadays, implemented object tracking solutions to AR are often based on computer vision (CV) methods such as SIFT, FERNS, SURF, FAST or other similar methods and their modifications (Bay, H.; Ess, A.; Tuytelaars, T. and Gool, L. V., 2008), (Rosten, E.; Porter, R.; Drummond, T., 2010), (Klein, G. and Murray, D., 2007), (Wagner, Reitmayr, Mulloni, Drummond, & Schmalstieg, 2010). Several tasks must be taken into consideration using the augmented reality systems that are based on computer vision methods:

1) Locate and track an object in the scene.

2) Display a virtual content depending on a trackable object orientation and position.

3) Ensure an opportunity to interact with the content.

While tracking an object in real environment conditions, several problems should be solved: illumination level, image transformations because of different camera perspectives, image quality, reflection and partial or full occlusion at the same time. As a result, less permanent features are detected and matches are found between different viewpoints of the same scene to accomplish reliable object tracking. A virtual content is not displayed, if the tracking is lost. Image processing speed is also the critical aspect for AR and must be accomplished in real-time.

Depending on the ultrasonic tracking method (Lukosiunas, E. et al., 2011) of the AR application field is a solution of position tracking. However, it is limited to the workspace and no orientation estimates are provided. Currently, the object motion tracking by using digital inertial sensors is an active research topic that is analysed in (Hol, J. D. et al., 2006), (Madgwick S. O., 2011), (Artemčiukas & Sakalaukas, 2014) works. A fast and irregular camera movement causes tracking errors and instabilities in the case of computer vision. These problems can be solved using inertial sensors to estimate rapid camera orientation changes. Using inertial sensors, camera tracking is a suitable method because of a high speed measurement acquisition. However, it is important to maintain the stability after a longer period of time. Sensors are affected by noise, drift and magnetic interference. By integrating and combining several sensor information disadvantages of separate sensors can be eliminated, using sensor fusion solutions (Sabatini, Quaternion-Based Extended Kalman Filter for Determining Orientation by Inertial and Magnetic Sensing, 2006), (Zhou, Duh, & Billinghurst, Sept. 2008), (Bleser & Stricker, 2008). Thus, reliable orientation estimates are provided.

This paper describes position and orientation estimation problems, which is critical in the field of the augmented reality, and proposes a way to improve that. In this research no specific computer vision method was proposed. However, assumptions were made that an object could be recognized and tracked in an image at 20 frames per second (with a disadvantage in speed). Wrong or unavailable orientation-position estimates, using computer vision tracking, can be improved or supplemented with additional estimates, using sensors. Orientation and position estimation is the main aspect analyzed in this work. To achieve better orientation-position estimates, a hybrid tracking method was designed using the Kalman filter. Computer vision (CV) and sensor fusion (SF) tracking information was simulated.

While representing a virtual content in the augmented reality environment, these aspects must be ensured without any interruption by a hybrid tracking method using the Kalman filter. Dynamic motion measurements of sensors are used to improve the information provided by the computer vision method. A conceptual diagram of data acquisition and processing obtained by sensors and the general purpose camera is presented in Fig. 1.

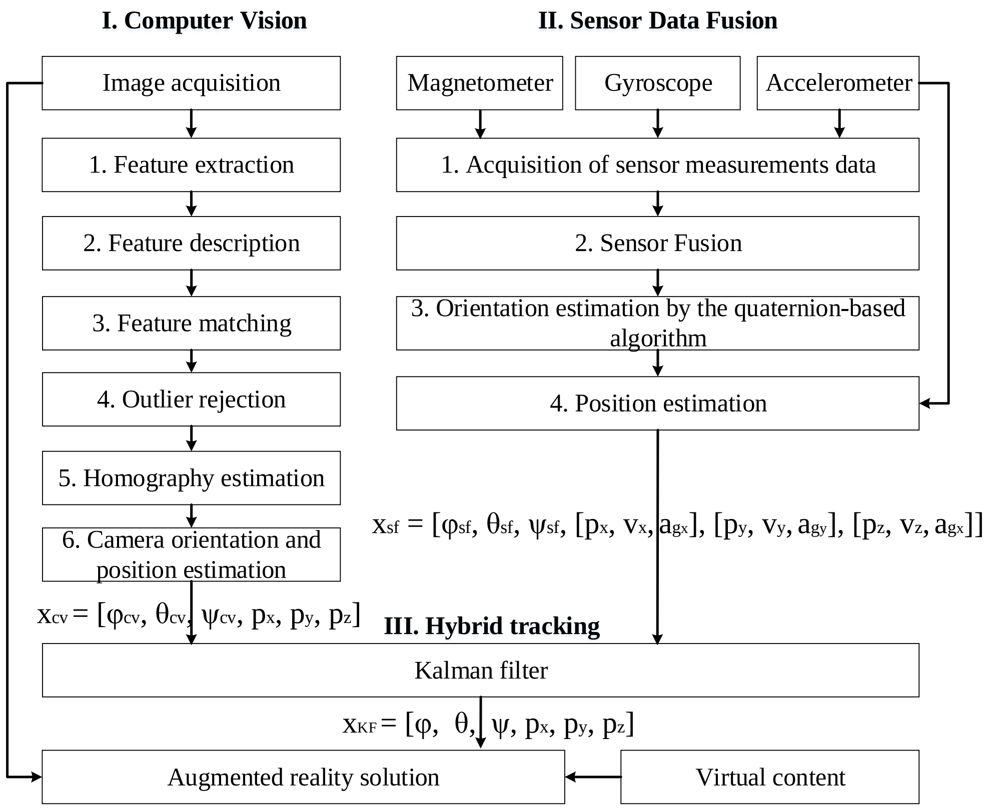


Fig. 1. Hybrid object tracking method using the Kalman filter: orientation and position estimation using computer vision and sensor fusion methods

This is a general model of a hybrid tracking method. The following assumptions on a further hybrid tracking method must be taken into consideration:

1) Calibration of a camera and sensors is performed off-line.

2) Sensors are rigidly attached to the camera, therefore, it is considered that coordinate systems coincide.

3) Processing of the computer vision (*CV*) and sensor data fusion (*SF*) methods is implemented on different threads. The frequency of processed data acquisition by the *CV* method is $f_{cv} = 20\ Hz$ ($\Delta t = 0.05$) and SF – $f_{sf} = 100$ Hz ($\Delta t = 0.01$).

4) Sensors attached to the camera move in the environment, not the object that can be tracked in the scene using *CV*.

The *CV* method provides relative information about the camera orientation-position. Accordingly, *CV* and *SF* orientation-position information is simulated from the common starting point. For instance, in the case of *CV*, relative camera orientation-position information is estimated from the object that is found and tracked in the scene and the sensor fusion solution provides this information directly from a camera motion.

Two main aspects are important from a user‘s perspective using the AR system:

1) The system must operate in real-time without any delay.

2) Even in a rapid movement and occlusion tracking must be robust without any jittering.

Object Tracking using Sensor Data Fusion

Orientation estimation using digital sensors is an urgent research topic. A digital accelerometer measures acceleration and gravity of a device. In the general case, this sensor is suitable to estimate an orientation of the object, depending on the Earth gravitational force. According to the measurements acquired by accelerometer, the orientation vector $a_{\phi,\theta} = [a_{\phi_t}, a_{\theta_t}]^T$ can be estimated by using expression (1):

$$a_{\phi,\theta} = \begin{bmatrix} a_{\phi_t} \\ a_{\theta_t} \end{bmatrix} = \begin{bmatrix} \arctan\left(a_{y_t} / \sqrt{a_{x_t}^2 + a_{z_t}^2}\right) \\ \arctan\left(a_{x_t} / \sqrt{a_{y_t}^2 + a_{z_t}^2}\right) \end{bmatrix}, \quad (1)$$

where a_{x_t}, a_{y_t}, a_{z_t} are accelerometer output at the current time moment with respect to x, y and the axis z. Sensor measurements in a stable state are affected by noise, therefore, a_{ϕ_t} (rotation around the axis x – roll) and a_{θ_t} (rotation around the axis y – pitch) orientation estimates can be wrong and unreliable. The gravity force does not provide information about the angle a_{ψ_t} (rotation around the axis z – yaw).

Angular rate measurements by a gyroscope are not affected by noise and do not accumulate errors. The object orientation vector $\omega_{\phi,\theta,\psi} = [\omega_{\phi_t}, \omega_{\theta_t}, \omega_{\psi_t}]^T$ is estimated by using expression (2):

$$\omega_{\phi,\theta,\psi} = \begin{bmatrix} \omega_{\phi_t} \\ \omega_{\theta_t} \\ \omega_{\psi_t} \end{bmatrix} = \begin{bmatrix} \omega_{\phi_{t-1}} + \omega_{x_t}\Delta t \\ \omega_{\theta_{t-1}} + \omega_{y_t}\Delta t \\ \omega_{\psi_{t-1}} + \omega_{z_t}\Delta t \end{bmatrix}, \quad (2)$$

where ω_{x_t}, ω_{y_t}, ω_{z_t} are the gyroscope angular rate at the current time moment t; $\omega_{\phi_{t-1}}$, $\omega_{\theta_{t-1}}$, $\omega_{\psi_{t-1}}$ are the estimated orientation at the earlier time moment $t-1$; Δt is time between measurements. Estimated orientation, using gyroscope angular rate measurements, is accurate only in a short period of time. After a longer period of time, a drift exponentially increases and errors are accumulated without any fixed reference system. It is a critical aspect for the augmented reality tracking system.

Direction b_ψ from the magnetometer can be determined using the following expression (3):

$$b_\psi = -arctan\left(\frac{m_{y_t}\, cos(a_{\phi_t})\, sin(a_{\theta_t}) - m_{z_t}\, sin(a_{\phi_t})}{m_{x_t}\, cos(a_{\theta_t}) + m_{y_t} sin(a_{\phi_t})\, sin(a_{\theta_t}) + m_{z_t}\, cos(a_{\phi_t})\, sin(a_{\theta_t})}\right), \qquad (3)$$

where m_{x_t}, m_{y_t}, m_{z_t} are magnetic field measurements by the magnetometer with respect to x, y, and z axes; a_{ϕ_t} and a_{θ_t} are the estimated orientation, using the accelerometer (1). One of the magnetometer disadvantages is that magnetic field measurements are affected by distortions, caused by ferromagnetic objects. These distortions can be compensated.

A combination of an accelerometer, gyroscope, and magnetometer, digital sensor measurements are used to ensure a reliable object orientation in a 3D space. The orientation drift using a gyroscope is eliminated by an accelerometer, which contributes in correcting ϕ and θ angles. A magnetometer ensures corrected ψ direction measurements in combination with an accelerometer. This is the main idea for sensor fusion using quaternion representation. Quaternion requires less calculation time, provides a reliable orientation estimation, and maintains the stability as compared to Euler angles or rotation matrix representation. Quaternion q is a four-element vector (4):

$$q = [q_0, q_1, q_2, q_3] = [w, xi, yj, zk], \qquad (4)$$

where $q_0(w)$ determines the rate of rotation; $q_1(x)$, $q_2(y)$, $q_3(z)$ are rotations in respect of x, y, and z axes. Quaternion-based algorithms for orientation estimation using sensors are explicitly analyzed in (Madgwick S. O., 2011), (Sabatini, Quaternion-Based Extended Kalman Filter for Determining Orientation by Inertial and Magnetic Sensing, 2006), therefore, no detailed analysis is provided in this work. Systems that use such orientation estimation methods are not limited to motion, specific environment, place, or occlusions, therefore, they have advantages over the computer vision methods.

Even though quaternion representation of orientation is more reliable, for simplicity, Euler angles are used instead of quaternions in further hybrid tracking experiments. The Euler angles $e_a = [\phi,\ \theta,\ \psi\ ]^T$ can be converted by quaternions using expression (5):

$$e_a = \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix} = \begin{bmatrix} tan^{-1}\left(\frac{2(q_2 q_3 - q_0 q_1)}{2q_0^2 + 2q_3^2 - 1}\right) \\ -sin^{-1}(2q_1 q_3 + 2q_0 q_2) \\ tan^{-1}\left(\frac{2(q_1 q_2 - q_0 q_3)}{2q_0^2 + 2q_1^2 - 1}\right) \end{bmatrix}. \qquad (5)$$

The position estimation is a difficult, but possible task using accelerometer measurement data. As mentioned before, the accelerometer measurements jointly measures acceleration and gravity, therefore, it is necessary to eliminate gravity to get a linear acceleration. If measurements in the array o sensors (accelerometer, gyroscope and magnetometer) are available, then the gravity vector $g = [g_x,\ g_y,\ g_z\ ]^T$ can be estimated, using the orientation represented in quaternion (6):

$$g = \begin{bmatrix} g_x \\ g_y \\ g_z \end{bmatrix} = \begin{bmatrix} 2q_1q_3 - 2q_0q_2 \\ 2q_0q_1 + 2q_2q_3 \\ q_0^2 - q_1^2 - q_2^2 + q_3^2 \end{bmatrix}, \tag{6}$$

where q_0, q_1, q_2, q_3 are quaternion elements that represent orientation; g_x, g_y, g_z are accelerometer gravity directions with respect to each axis. The estimated orientation must be accurate, using the quaternion representation. Even small errors in the orientation estimation, which is used to calculate the gravity vector, can cause large errors in a linear acceleration. The linear acceleration vector a_g with the eliminated gravity g from the accelerometer output can be estimated using expression (7):

$$a_g = \begin{bmatrix} a_{g_x} \\ a_{g_y} \\ a_{g_z} \end{bmatrix} = \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} - \begin{bmatrix} g_x \\ g_y \\ g_z \end{bmatrix}, \tag{7}$$

Using the linear acceleration a_g, the velocity v_t and position p_t vectors are estimated by mean s of each axis using expressions (8) and (9):

$$v_t = v_{t-1} + {a_g}_t \Delta t, \tag{8}$$

$$p_t = p_{t-1} + v_t \Delta t + {a_g}_t \frac{\Delta t^2}{2}, \tag{9}$$

where Δt is time between measurements; $v_0 = 0$ and $p_0 = 0$, as $t = 1$ at the initial time moment. Since accelerometer measurements are affected by noise, it cannot be efficiently used for position estimation. For further experiments, the estimated orientation and position-velocity-acceleration vector x_{sf} are modelled using expression (10):

$$x_{sf} = \left[\phi_{sf}, \theta_{sf}, \psi_{sf}, [p_x, v_x, a_{g_x}], \left[p_y, v_y, a_{g_y}\right], [p_z, v_z, a_{g_z}]\right], \tag{10}$$

where $\phi_{sf}, \theta_{sf}, \psi_{sf}$ are orientation estimates, based on the sensor data fusion in respect of x, y and z axes; $[p_s, v_s, a_{g_s}]$ are position, velocity, and acceleration vector is obtained by using sensor measurements, where s is x, y, and z axes, respectively.

Object Tracking using Computer Vision

Computer Vision methods use feature extraction (detection) and description as a primary analysis aspect to find interest points in an image and matching to perform object tracking. They enable to estimate a relative orientation and position of the camera using the RANSAC probability method. From the geometric perspective, it can be explained by using a pinhole camera model that is widely used and analyzed in computer vision researches. It defines a relationship between the 3D point $P = [X, Y, Z]^T$ from the scene and corresponding the 2D projection $p = [x, y]^T$ onto the image plane. Mapping from 3D to 2D is called a perspective projection and can be expressed by (11):

$$\underbrace{\begin{bmatrix} x \\ y \\ 1 \end{bmatrix}}_{\boldsymbol{p}} = \underbrace{\begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix}}_{\substack{\text{vidiniai} \\ \text{parametrai}}} \left(\underbrace{\begin{bmatrix} R_{11} & R_{12} & R_{13} & T_1 \\ R_{21} & R_{22} & R_{23} & T_2 \\ R_{31} & R_{32} & R_{33} & T_3 \end{bmatrix}}_{\substack{\text{išoriniai} \\ \text{parametrai}}} \underbrace{\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}}_{\boldsymbol{P}} \right), \tag{11}$$

where f_x, f_y is the focal length; c_x, c_y is the optical center of the camera. Intrinsic parameters are used to remove distortions. The extrinsic parameter is a transformation matrix in the camera coordinate system, which consists of the rotation matrix $R_{3\times3}$ for orientation and the translation vector $T_{3\times1}$ for position. Computer vision methods focus on estimating this fundamental transformation matrix. The rotation matrix can be converted to Euler angles by expression (12):

$$e_r = \begin{bmatrix} \phi_{cv} \\ \theta_{cv} \\ \psi_{cv} \end{bmatrix} = \begin{bmatrix} tan^{-1}\left(\frac{R_{23}}{R_{33}}\right) \\ -sin^{-1}(R_{13}) \\ tan^{-1}\left(\frac{R_{12}}{R_{11}}\right) \end{bmatrix}. \tag{12}$$

In the case of computer vision, the orientation and position vector x_{cv} is modelled by means of expression (13):

$$x_{cv} = [\phi_{cv}, \theta_{cv}, \psi_{cv}, p_x, p_y, p_z], \tag{13}$$

where $\phi_{cv}, \theta_{cv}, \psi_{cv}$ are the orientations converted from the rotation matrix ($R_{3\times3}$) to Euler angles and p_x, p_y, p_z are position coordinates from the translation vector ($T_{3\times1}$).

Hybrid Tracking Method using the Kalman Filter Experiments and Results

Taking assumptions into consideration, the Kalman filter (*KF*) is applied to simulate orientation-position information. The *KF* algorithm is recursive and widely used in object trajectory prediction, control, tracking, collision-warning systems, image processing, sensor fusion, etc. *KF* consists of prediction (process model) (14-15) and update (measurement model) (16-18) steps:

1) State prediction $\hat{x}_k$ (14):

$$\hat{x}_k = A\bar{x}_{k-1} + Bu_k + w_k, \tag{14}$$

2) State covariance $\hat{P}_k$ prediction (15):

$$\hat{P}_k = A\bar{P}_{k-1}A^T + Q, \tag{15}$$

3) Factor K_k calculation to correct the state prediction $\hat{x}_k$ (16):

$$K_k = \hat{P}_k\, H^T\left(H\hat{P}_k\, H^T + R\right)^{-1}, \tag{16}$$

4) Update of the state estimate $\bar{x}_k$ using the measurement w_k (17):

$$\bar{x}_k = \hat{x}_k + K_k(z_k - H\hat{x}_k), \tag{17}$$

5) Covariance $\bar{P}_k$ update (18):

$$\bar{P}_k = (I - K_k H)\hat{P}_k, \tag{18}$$

where $\hat{x}_k$ is a state prediction vector affected by noise w_k; $\bar{x}_k$ is an update vector; $z_k = Hx_k + v_k$ is a measurement vector affected by noise v_k; $w_k \sim N(0, Q)$, $v_k \sim N(0, R)$ are respectively, process prediction and measurement update independent Gaussian noises; A is a state transition matrix; $\hat{P}_k$, $\bar{P}_k$ are respectively prediction and update state covariance matrix; $Q = E[w_k w_k^T]$, $R = E[v_k v_k^T]$, respectively, are independent process and measurement noise covariance matrices; H is a measurement matrix; I is an identity matrix. In the step of update, the difference between the measurement and prediction states is compensated and the new estimates determined. The convergence rate of *KF* depends on Q and R values; a decreased value of Q or R shows the confidence either in the process or measurement steps.

When analyzing independent innovation $\hat{y}_k$ (19) or residual $\bar{y}_k$ (20) sequences, the *KF* efficiency can be determined, which is a reliable quality indicator:

$$\hat{y}_k = z_k - H_k \hat{x}_k, \tag{19}$$
$$\bar{y}_k = z_k - H_k \bar{x}_k. \tag{20}$$

In an ideal case, the mean value of dynamic systems' innovation $\hat{y}_k$ and residual $\bar{y}_k$ has to be zero or near to zero.

Next, for simplicity, *SF* vector x_{sf} are separated into two parts:

a) orientation vector x_{sf}^o;

b) position-velocity-acceleration vector $x_{sf}^p = \left[[p_x, v_x, a_{g_x}], \left[p_y, v_y, a_{g_y}\right], [p_z, v_z, a_{g_z}]\right]$.

CV vector x_{cv} is also divided in to orientation $x_{cv}^o = [\phi_{cv}, \theta_{cv}, \psi_{cv}]$ and position $x_{cv}^p = [p_x, p_y, p_z]$ parts. From here some matrices are denoted by a superscript "o" for orientation and a superscript "p" for position or position-velocity-acceleration vectors to avoid confusion (21-22):

$$A^o = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, A^p = \begin{bmatrix} 1 & \Delta t & \Delta t^2/2 \\ 0 & 1 & \Delta t \\ 0 & 0 & 1 \end{bmatrix}, \tag{21}$$
$$H^o = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, H^p = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}. \tag{22}$$

Two different *KF* perspectives are used for estimating orientation and position. *CV* has a slower data processing rate, therefore, faster *SF* information available is used for prediction between *CV* samples. According to the described orientation and position estimation scenarios, *KF* is applied using prediction and update equations. In the orientation estimation scenario, three orientation states ϕ, θ, ψ are estimated using *KF* for hybrid tracking. The simulated camera orientation (ϕ angle), using *SF* and *CV*, is presented in Fig. 2.

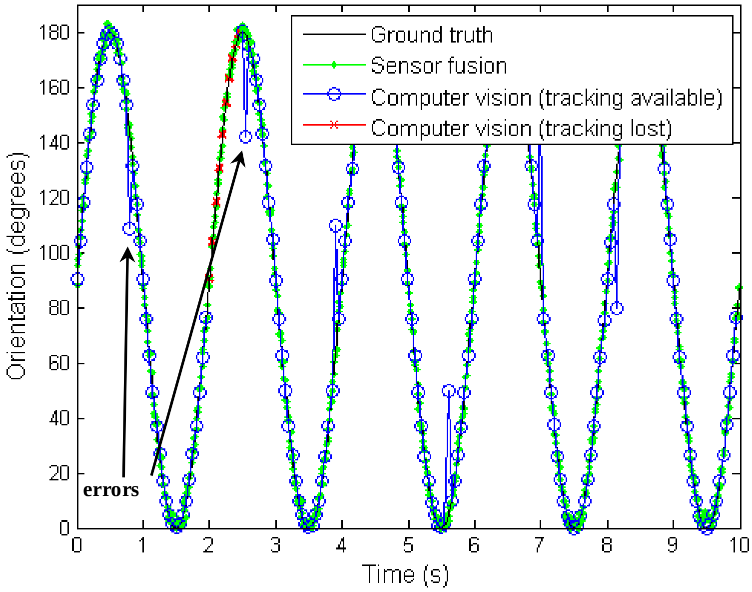


Fig. 2. Simulated *SF* and *CV* orientation with modelled outliers and unavailable orientation segments using *CV*

Initial tracked object orientation is 90 degrees. Processed data are acquired in constant time intervals from camera and sensors. Similar orientation results would be obtained for θ and ψ angles. Camera orientation is simulated in rapid motion. Even though most of the time orientation using *CV* is available, in some cases, tracking is improperly estimated, which causes spikes or it can be lost (red crosses) because of the occlusion.

The hybrid object tracking method, using the Kalman filter starts after the orientation information has been acquired, using the *CV* method, and is used as the initial state $\bar{x}_0$ (starting point) in the prediction equation. The update vector $\bar{x}_{k-1}$ in prediction (17) corresponds to the computer vision orientation vector x_{cv}^{o} and the measurement z_k corresponds to the sensor fusion orientation vector x_{sf}^{o}. In the general case, a better confidence is assigned to available *CV* information (Q for process), rather than SF (R for measurement) (23):

$$Q = \begin{bmatrix} 1 \cdot 10^{-4} & 0 & 0 \\ 0 & 1 \cdot 10^{-4} & 0 \\ 0 & 0 & 1 \cdot 10^{-4} \end{bmatrix}, R = \begin{bmatrix} 10 & 0 & 0 \\ 0 & 10 & 0 \\ 0 & 0 & 10 \end{bmatrix}. \tag{23}$$

The update state $\bar{x}_k$ using the *SF* measurement z_k is applied in the prediction step with the same confidence as *CV* information, if the orientation vector $\bar{x}_{k-1}$ using *CV* is unavailable for the state prediction $\hat{x}_k$. Also, the following conditions are introduced to determine the confidence, when a wrong *CV* orientation vector is acquired (24):

$$\begin{cases} |\hat{y}_k| < z_k \cdot z_{TH} & \text{trust is given to the process,} \\ |\hat{y}_k| > z_k \cdot z_{TH} & \text{trust is given to the measurement,} \end{cases} \tag{24}$$

where z_{TH} is the determined 5 % threshold parameter. Innovation $|\hat{y}_k|$ comparison with z_k takes place as measurements of *SF* are always available. If the error in *CV* is critical, innovation exceeds the threshold of measurement z_k, therefore, a better confidence is provided to measurement. In real-life conditions, the existing errors in *CV* provides considerable differences as compared to the *SF* orientation information.

If *CV* information is available without any errors, innovation does not exceed a threshold, as it provides similar results for *SF* orientation. The estimated orientation using the Kalman filter for hybrid tracking is presented in Fig. 3.

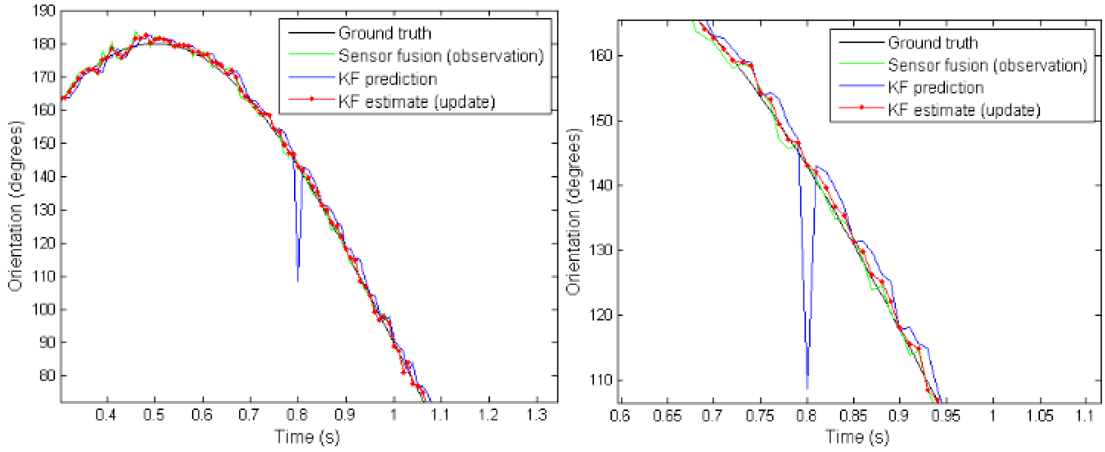


Fig. 3. Hybrid tracking method, using the Kalman filter, for estimating orientation

A spike in the *CV* orientation is successfully eliminated using *KF*. The same applies to unavailable orientation information from *CV*. The innovation results in the case of orientation are presented in Fig. 4.

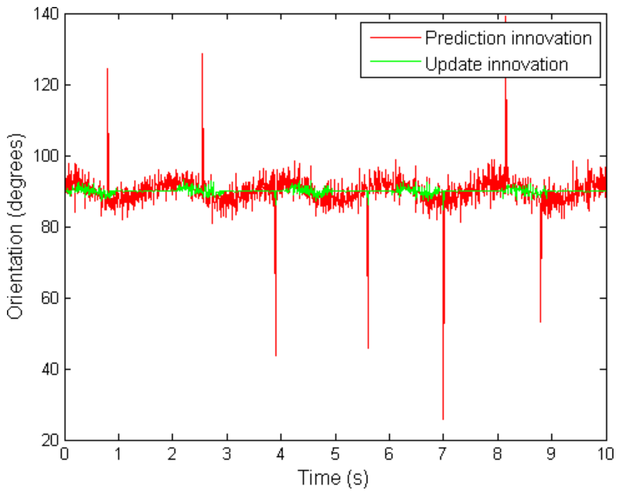
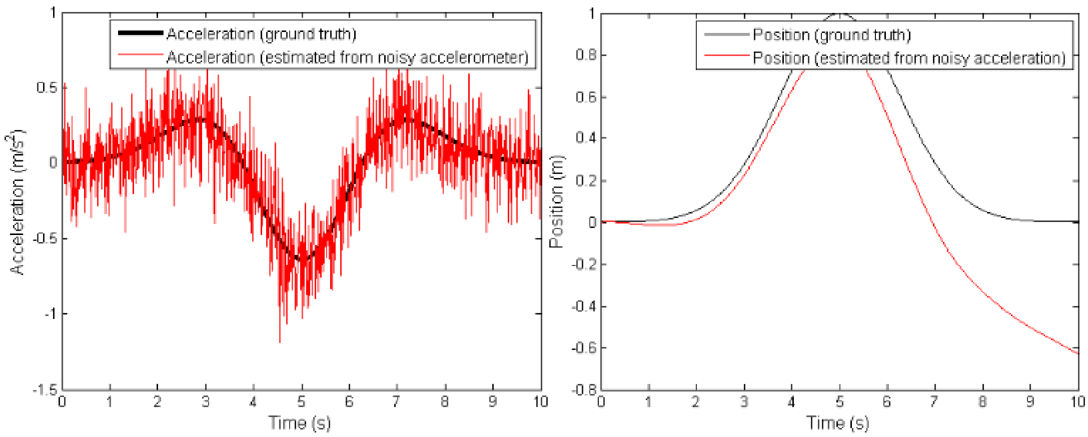


Fig. 4. Prediction of orientation and update innovation sequences

Spikes in the innovation are errors from the *CV* orientation information and are taken into consideration while estimating the orientation by applying hybrid tracking method using the Kalman filter.

In the position estimation scenario only one coordinate is tracked. For estimating the position *SF* information is used in the process model and *CV* information in the measurement model. A^p (21), also known as a constant acceleration model (for the process model) is used to calculate only a 1-axis vector of position, velocity, and acceleration. For the other two axes the same model should be applied as well. In the case of measurement part, the interest is held only in position. Velocity and acceleration are not observed, therefore, H^p is used according to expression (22). The simulated noisy acceleration and estimated position are presented in Fig. 5.



(a) (b)

Fig. 5. Simulated acceleration for estimating position: a) noisy acceleration (normal distribution with = 0.2) for estimating position; b) drifted position estimates from noisy acceleration compared to the ground truth

Positive and negative values in the diagrams show a direction of acceleration and position. In the process model ($\bar{x}_{k-1}$) position-velocity-acceleration information is estimated from acceleration, and in the measurement model (z_k), position is acquired from *CV*. A better confidence is provided for a computer vision information, since using noisy acceleration measurements, position estimates accumulate considerable errors. Position innovation sequences are presented in Fig. 6.

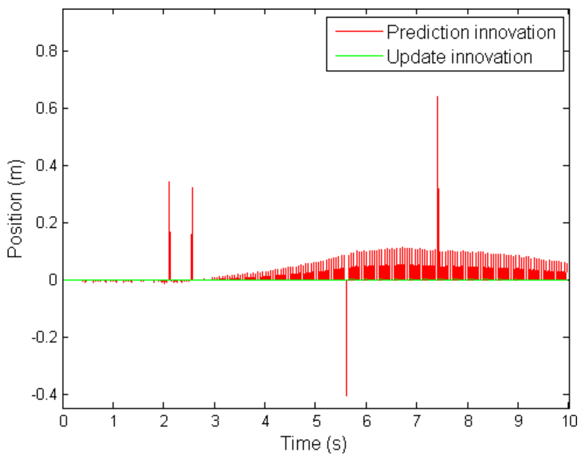


Fig. 6. Position prediction and update innovation sequences

To avoid an increasing difference between the process and measurement estimates, modifications are made in prediction of equation (25) by adding a control vector (25, 26, 27):

$$\hat{x}_k = A^p\,\bar{x}_{k-1} + Bu_k + w_k, \tag{25}$$

$$B = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, u_k = \begin{bmatrix} \hat{y}_k^m \\ 0 \\ 0 \end{bmatrix}, \tag{26}$$

$$\hat{y}_k^m = \hat{y}_k + \frac{f_{cv}}{f_{sf}} \cdot \frac{\sum_{i=k-n+1}^{k}(z_i - z_{i-1})}{(n-1)}, \tag{27}$$

where B is a control matrix; u_k is a control vector; $n = 4$ are four last available measurements by *CV*. By adding a control vector consisting of the modified innovation $\hat{y}_k^m$, it is ensured that estimation of the position by *SF* will not diverge among *CV* samples. A modified innovation is calculated using the previously available z_k measurements from *CV* and the current estimated position from *SF*, up to the next available *CV* position information. The position estimated by the hybrid tracking method using the Kalman filter is presented in Fig. 7.

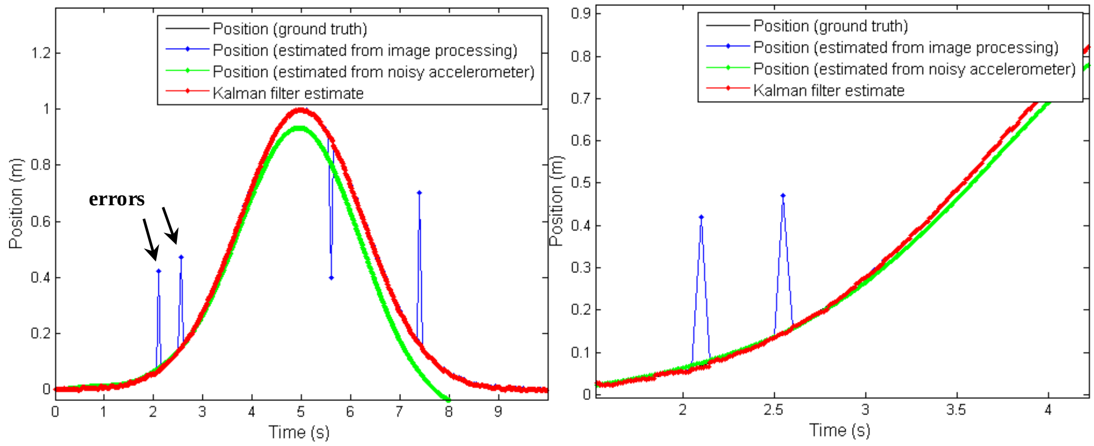


Fig. 7. Hybrid tracking method using the Kalman filter for estimating position

The main demand for the augmented reality hybrid tracking method is in the case of a lost object tracking using *CV* to provide camera orientation-position information from additional sources – inertial sensors. Summarized results of the accomplished experiments are presented in Table II and Table III.

TABLE II. Results of the estimating orientation mean (μ), standard deviation (σ), root mean square error (*RMSE*).

Parameter	**Estimation of orientation (degrees)**			
	GT	***SF***	***CV***	***KF***
μ	90,00	90,30	88,55	90,28
σ	63,67	63,73	63,84	63,68
RMSE	-	89,73	90,27	89,79

TABLE III. Results of the estimating position mean (μ), standard deviation (σ), root mean square error (*RMSE*).

Parameter	**Estimation of position (meters)**			
	GT	***SF***	***CV***	***KF***
μ	0,31	0,34	0,32	0,31
σ	0,35	0,38	0,36	0,35
RMSE	-	0,04	0,06	0,003

GT denotes a ground truth. In the presented results for estimating orientation-position *KF* for hybrid tracking show the best results: the mean and standard deviation is nearest to the ground truth value. In the case of root mean square error (*RMSE*) in the estimation of orientation the error is smallest from 90 degrees (the original state in object tracking). In the case of position, it is near to zero value, which is a reliability indication of the estimated results. RMSE is calculated using expression (28):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_{GT_i} - x_{EST_i}\right)^2}, \quad (28)$$

where n is the amount of data; x_{GT} are specific ground truth values (orientation or position), and x_{EST} is a specific estimated orientation with respect to ϕ, θ or ψ angles; or a position value with respect to x, y, or z axes using different approaches: sensor fusion data, computer vision, and hybrid object tracking method using the Kalman filter. In order to calculate percentage change of *RMSE* from ground truth orientation and position data *RMSPE* (or *%RMSE*) is calculated using expression (29):

$$RMSPE = \frac{\sqrt{\sum_{i=1}^{n}\left(x_{GT\,i} - x_{EST\,i}\right)^2}}{\mu_{GT}} \cdot 100\% , \tag{29}$$

where μ_{GT} is respectively ground truth average of orientation or position data. The proposed hybrid object tracking using the Kalman filter shows an increased tracking efficiency and the estimated orientation error is $RMSPE_{KF}^{o} = 0{,}24\%$, in the case of only sensor data fusion – $RMSPE_{SF}^{o} = 0{,}30\%$, and in the case of only computer vision method – $RMSPE_{CV}^{o} = 0{,}30\%$. The estimated position error in the case of hybrid object tracking using the Kalman filter is $RMSPE_{KF}^{p} = 0{,}96\%$, in the case of only sensor data fusion – $RMSPE_{SF}^{p} = 13{,}06\%$, and in the case of only computer vision method – $RMSPE_{CV}^{p} = 19{,}75\%$.

Other researches related to the tracking approaches, provide neither their experimental results nor ground truth values in a numeric form to make objective comparisons. Even though this research focuses on a hybrid tracking method, solution can be easily adapted for the development of interaction devices.

In the hybrid tracking case, the content can be maintained intact in the same position and orientation independently of the used computer vision method. If the solution were based only on the computer vision method, such a virtual content alignment would fail. This is a critical problem and should be solved to avoid unreliable usability of the augmented reality applications. A general hybrid tracking research application is presented in Fig. 8.

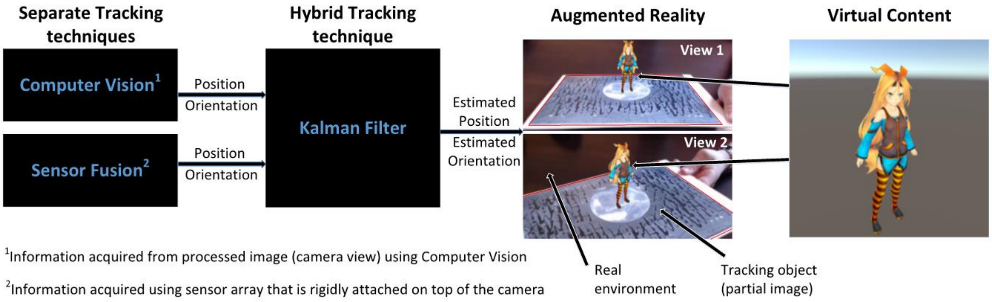


Fig. 8. Hybrid tracking method using the Kalman filter in the augmented reality

Specifically such a hybrid tracking approach was applied in the field of internet of things, provided in Fig. 9.

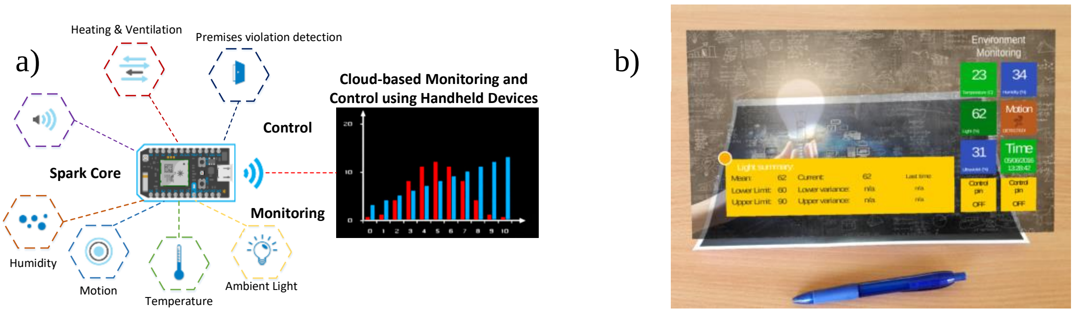


Fig. 9. a) Spark Core cloud-based infrastructure for AR Internet of Things solution; b) The augmented reality internet of things user interface and real-time data parsing from the cloud

In such an augmented reality for internet of things application scenario, motion, temperature, humidity, and light intensity sensor measurements are sent to the cloud. In the presented augmented reality scenario, the *Unity3D* game development environment and *Vuforia* plugin were used to develop markerless AR *IoT* indoor solution with a predefined image target.

GENERAL CONCLUSIONS

1) Accomplished analysis of feature extraction and classification methods it was determined that these methods tries to solves features acquired from image redundancy problem and transforming it into a reduced feature vector that has enough information to uniquely recognize and track specific object in the environment. There are no universal feature extraction method that would fit any type of object to be tracked or application field, as there exist other requirements in different application fields, specific tracking object characteristics and environment conditions on which depends feature accessibility. Based on the carried out experiments, from the speed perspective it has been determined that feature extraction and matching takes 4 times slower than the *SURF* method and 11 times slower than *FAST*. In the augmented reality systems object tracking must take place in real-time. To estimate *SIFT*, *SURF* and *FAST* feature extraction stability, repeatability criterion was used. While changing the scale of original image size the *SIFT* repeatability criterion was higher by 15-30% than the *SURF* method and by 35–55% higher than *FAST*. By changing the original image size by ±30% tendencies stay similar: the *SIFT* method repeatability criterion has increased by 15–30% more than the *SURF* method and 50–55% more than *FAST*. In the case of image rotation, the *SIFT* method repeatability criterion was higher by 40% as compared with *SURF* and *FAST* methods. In the case of image translations, *SIFT* and *SURF* repeatability criteria results are similar, but by 4–20% higher than the *FAST* method.

2) The analysis has showed that using separate sensor measurement data to determine object orientation is not a reliable solution. In the analytical-experimental approach, accelerometer, gyroscope, and magnetometer sensor measurements were investigated, as well as a fused sensor data case by applying a gradient descent method to quaternion representation of orientation, when the sensor array is attached to the camera. After the experiments and calculation results, it has been determined that, by using the gradient descent method, some sensor measurement disadvantages can be compensated and the estimated orientation accuracy and reliability improved, avoiding divergence, noise, and decreasing delay, which is a frequent case while using computer vision methods. It has been determined that it is purposeful to use sensor data fusion to supplement unavailable object tracking estimates or to improve them. These estimates

have been acquired based on computer vision methods, when tracking is disrupted, caused by a fast camera motion or wrongly estimated position and orientation information due to different image transformations.

3) The proposed hybrid object tracking method using the Kalman filter consists of sensor data fusion (to track camera) and computer vision (to track image) methods on which based orientation and position information was imitated. The results of hybrid object tracking method were experimentally evaluated and compared with only computer vision and only sensor data fusion cases. The proposed hybrid object tracking method using the Kalman filter shows an increased tracking efficiency, and the estimated orientation error is 0,24%, in the case of only sensor data fusion is 0,30%, and in the case of only computer vision method is 0,30%. The estimated position error in the case of hybrid object tracking using the Kalman filter is 0,96%, in the case of only sensor data fusion is 13,06%, and in the case of only computer vision method is 19,75%.

4) The proposed hybrid object tracking method using Kalman filter applied for mobile devices allows continuously display user interface for internet of thing in the augmented reality environment, but also a separate hybrid object tracking method part can be adapted to develop interaction devices, which allow us to expand and improve interaction with the digital content or other technical equipment, enabling different modes and application possibilities, therefore, proposed hybrid object tracking characterizes with universality.

HIBRIDINIS OBJEKTŲ SEKIMO METODAS PAPILDYTOS REALYBĖS SISTEMOSE NAUDOJANT KALMANO FILTRĄ

ĮVADAS

Papildyta realybė (angl. *Augmented Reality*) yra sritis, išsivysčiusi iš virtualiosios realybės, kurioje vartotojas mato realioje aplinkoje virtualų turinį ir turi galimybę su juo sąveikauti. Papildytos realybės galimos taikymo sritys yra medicina, švietimas, gamyba, pramogos, rinkodara ir kt. Papildyta realybė suteikia galimybę matyti tikrąjį pasaulį įterpiant į jį virtualius objektus ar kitą informaciją. Tokiu būdu objektai nėra pakeičiami, o integruojami į realybę. Atliekant objektų sekimą aplinkoje dažniausiai naudojami kompiuterinės regos metodai. Jie atlieka sudėtingą informacijos iš realios aplinkos išgavimo ir apdorojimo procesą, norint suteikti patikimą informaciją, kaip ir kur vartotojui turi būti pateiktas virtualus turinys. Efektyvus objektų atpažinimas ir sekimas yra esminis uždavinys, sprendžiamas papildytos realybės srityje norint patikimai atvaizduoti virtualų turinį sekamo objekto atžvilgiu. Šiuo metu papildytos realybės sistemos dažniausiai naudojamos mobiliuosiuose įrenginiuose, todėl reikalingas sprendimo būdas, kuris patikimai įvykdytų atpažinimo, sekimo ir virtualaus turinio atvaizdavimo užduotis. Inercinių jutiklių sistemos šiuo metu dažnai naudojamos dėl galimybės įvertinti įrenginių orientaciją, todėl jų taikymas yra perspektyvus papildytos realybės srityje. Pagrindinės papildytos realybės tyrimų sritys susijusios su tokiais aspektais:

a) Grafikos perteikimo techninė ir programinė įranga.

b) Sekimo metodai, kurie leidžia tinkamoje padėtyje pateikti virtualų turinį sekamo objekto atžvilgiu.

c) Sekimo metodo kalibravimo ir registravimo priemonės, skirtos tiksliai suderinti realų ir virtualų vaizdą vartotojo atžvilgiu.

d) Rodymo techninė įranga norint sujungti virtualų vaizdą su realaus pasaulio vaizdu.

e) Kompiuterinė techninė įranga apdoroti papildytos realybės algoritmus.

f) Sąveikos metodai, kurie nurodo kaip vartotojas gali manipuliuoti papildytos realybės virtualiu turiniu.

Paprastai pilno papildytos realybės sprendimo kūrimas apima techninės, programinės įrangos ir metodų iš punktuose a)–f) minėtų aspektų integraciją. Objektų pozicijos ir orientacijos sekimo metodai yra pagrindinė nagrinėjama problema daugelio mokslinių tiriamųjų darbų. Šie metodai naudojami papildytos realybės srityje ir vis dar turi daug neišspręstų problemų, todėl hibridinių objektų sekimo metodų sudarymas yra tikslingas, kai naudojama tiek kompiuterinės regos, tiek jutikių duomenų sujungimo atveju gauta pozicijos ir orientacijos informacija apie sekamą objektą, siekiant patikimiau įvertinti tiek objekto poziciją, tiek objekto orientaciją erdvėje tuo pačiu metu. Kitos tyrimų problemos yra susijusios su sąveikos metodais, kurių pagrindu manipuliuojama skaitmeniniu turiniu.

Tyrimo problemos aktualumas

Papildyta realybė yra vizualizavimo technika, kuri plačiai naudojama daugelyje mobiliųjų programėlių, dažniausiai sekant dirbtinį objektą vaizdo požymių išskyrimo ir apdorojimo metodų pagrindu, pavyzdžiui, naudojant kvadratinį žymeklį (angl. *markers*). Vaizdo požymių išskyrimo ir apdorojimo metodo pagrindu paskaičiuojama, kurioje padėtyje (pozicijoje ir orientacijoje) turi būti atvaizduotas 2D/3D virtualus turinys vartotoją supančioje realioje aplinkoje. Pagrindinės problemos, naudojant žymeklius, vartotojo ar objektų iš aplinkos okliuzijos. Dėl šių okliuzijų dažniausiai dingsta 3D virtualus turinys, todėl jos turi neigiamą įtaką mobiliajai programai naudoti. Kai kurie kompiuterinės regos metodai leidžia išspręsti dalinės okliuzijos problemas atvaizduojant virtualų turinį, tačiau būtina įvertinti šių metodų greitį bei tinkamumą, nes užduotys turi būti vykdomos realiu laiku. Žymeklių sekimo metodas sumažina skaičiavimų reikalavimus, tačiau turi apribojimų dėl sekamo objekto dydžio vaizde bei nutrūkstančio sekimo, kai žymeklis nėra matymo lauke. Pagrindinė kompiuterinės regos metodų realaus laiko sekimo sistemose problema – aplinkos kompleksiškumas ir sekamo objekto judėjimas. Pavyzdžiui, objektas gali atsiskirti, susilieti dėl dalinių okliuzijų ar vaizdo triukšmo, objekto vaizdas gali keistis dėl skirtingo apšvietimo, o didesniu atstumu esančių objektų požymiai nėra patikimai rekonstruojami, todėl neefektyviai paskaičiuojama sekamo objekto orientacija bei padėtis. Greitas arba netolygus kameros judėjimas sukelia vaizdo sekimo sutrikimų. Tokie trūkumai gali būti pašalinami naudojant inercinius jutiklius. Inercinių jutiklių matavimų informacija suteikia galimybę įvertinti staigius objekto, pavyzdžiui, įrenginio kameros orientacijos bei pozicijos pokyčius, kurie gali atsirasti naudotojui judinant įrenginį, tačiau atskira jutiklių informacija nėra tiksli ir patikima. Jutiklių matavimai paveikiami triukšmo, nuokrypių ir magnetinės interferencijos, todėl yra poreikis sudaryti efektyvų orientacijos ir pozicijos įvertinimo modelį.

Tyrimo objektas

Darbo tyrimo objektas – objektų sekimo metodai papildytos realybės sistemose, leidžiantys įvertinti objektų orientaciją ir poziciją realioje erdvėje, požymių išskyrimo iš vaizdo bei apdorojimo ir jutiklių duomenų sujungimo pagrindu.

Tyrimo tikslas

Darbo tyrimo tikslas – pasiūlyti hibridinį objekto sekimo metodą naudojant Kalmano filtrą papildytos realybės srityje, požymių išskyrimo iš vaizdo ir jutiklių duomenų sujungimo metodų pagrindu, siekiant pagerinti objektų orientacijos ir pozicijos sekimo tikslumą realioje erdvėje.

Tyrimo uždaviniai

Tikslui įgyvendinti keliami tokie darbo uždaviniai:

1. Atlikti objektų sekimo metodų, kompiuterinės regos ir jutiklių duomenų sujungimo pagrindu, tyrimą bei pateikti taikymo rekomendacijas papildytos realybės srityje.
2. Išanalizuoti analitiniu-eksperimentiniu būdu inercinių jutiklių taikymo galimybes bei jutiklių orientacijos duomenų sujungimo metodus, siekiant pritaikyti objekto sekimo informaciją ne tik papildytos realybės sistemose, bet ir sukonstruoti sąveikos įrenginį, skirtą manipuliuoti skaitmeniniu turiniu.
3. Pasiūlyti hibridinį objekto sekimo metodą naudojant Kalmano filtrą papildytos realybės srityje, pasižymintį papildančiomis savybėmis orientacijos ir pozicijos įvertinime, lyginant su ne hibridinių metodų naudojimu, kai informacija galimai neprieinama, bei užtikrinantį pagerintą objektų sekimo sprendimą tikslumo ir patikimumo atžvilgiu.

4. Palyginti pasiūlyto hibridinio objekto sekimo metodo, naudojant Kalmano filtrą, tyrimo rezultatus su baziniais orientacijos ir pozicijos duomenimis ir pritaikyti šį sprendimą papildytos realybės daiktų interneto srityje, kur būtų užtikrintas sukurtos vartotojo sąsajos, skirtos daiktų internetui, nenutrūkstamas atvaizdavimas realiu laiku, esant greitiems kameros judesiams ar okliuzijoms aplinkoje.

Tyrimo metodika

Analizuojant mokslinius tyrimus objektų pozicijos ir orientacijos sekimo erdvėje atžvilgiu, naudoti informacijos paieškos, sisteminimo, analizės, lyginamosios analizės ir apibendrinimo metodai. Atliktų tiek teorinių, tiek empirinių tyrimų pagrindu sukonstruotas sąveikos įrenginio prototipas ir pasiūlytas hibridinis objektų sekimo metodas naudojant Kalmano filtrą. Eksperimentinio tyrimo metodu atliktas skaitmeninis signalų apdorojimas ir statistinė tyrimų rezultatų analizė, o gautiems rezultatams įvertinti naudotas palyginimo ir apibendrinimo metodas.

Darbo mokslinis naujumas ir jo reikšmė

Rengiant disertaciją buvo gauti šie mokslui nauji rezultatai:

1. Daugelis nagrinėtų objekto pozicijos ir orientacijos sekimo metodų tyrimų labiau teoriniai, aprašomojo pobūdžio arba analizuojama tik dalinė problema: a) pozicijos ir orientacijos įvertinimas tik kompiuterinės regos metodų atvejais; b) tik pozicijos arba tik orientacijos įvertinimas jutiklių duomenų sujungimo atvejais. Nėra sisteminių tyrimų, leidžiančių kompiuterinės regos metodų trūkumus sumažinti, kai objekto sekimas nutrūksta dėl besikeičiančių išorės savybių po vaizdo transformacijų, okliuzijų ar kitų aplinkos sąlygų, naudojant papildomus objektų sekimo metodus, pavyzdžiui, jutiklių duomenų sujungimą, tačiau išskirtinai šioje disertacijoje toks tyrimas pateiktas.

2. Pasiūlytas hibridinis objektų sekimo metodas naudojant Kalmano filtrą pasižymi papildančiomis savybėmis pozicijos ir orientacijos įvertinimo atžvilgiu, kuriame pašalinti atskirai naudojamų objekto sekimo metodų trūkumai kaip triukšmas, nuokrypiai ir sekimo sutrikimai. Šie sekimo sutrikimų gerinimai yra svarbūs dėl problemų esančių tiek vaizdo požymių išskyrimo ir apdorojimo, tiek jutiklių matavimų duomenų sujungimo metoduose. Hibridinio objektų sekimo metodo rezultatai, eksperimentiškai įvertinti ir palyginti su imituotais kompiuterinės regos bei jutiklių duomenų sujungimo metodo duomenimis, rodo padidėjusį sekimo tikslumą. Hibridinio objekto sekimo metodo naudojant Kalmano filtrą orientacijos įvertinimo paklaida siekia tik $RMSPE_{KF}^{o} = 0{,}24\%$, kai tuo tarpu tik jutiklių duomenų sujungimo atveju $RMSPE_{SF}^{o} = 0{,}30\%$, o tik kompiuterinės regos atveju $RMSPE_{CV}^{o} = 0{,}30\%$. Pozicijos įvertinimo paklaida siekia $RMSPE_{KF}^{p} = 0{,}96\%$, tik jutiklių duomenų sujungimo atveju – $RMSPE_{SF}^{p} = 13{,}06\%$, o tik kompiuterinės regos atveju – $RMSPE_{CV}^{p} = 19{,}75\%$.

3. Atliktas hibridinis objektų sekimo metodas naudojant Kalmano filtrą tyrimas universalus tuo, kad gali būti taikomas ne tik papildytos realybės sistemose, bet taip pat parodyta, kad atskira jutiklių duomenų sujungimo tyrimo dalis panaudota konstruojant nauju naudojimo būdu pasižymintį sąveikavimo įrenginį.

Darbo rezultatų praktinė reikšmė

1. Pasiūlytas hibridinis objekto sekimo metodas naudojant Kalmano filtrą yra aktualus daugelyje praktinių taikymo sričių, tačiau tyrime numatyta pagrindinė taikymo sritis yra papildyta realybė. Šiuo metodu siūlomas patikimas objektų

orientacijos ir pozicijos įvertinimas erdvėje, kuriuo užtikrinamas virtualaus turinio pateikimas realaus vaizdo kontekste nepertraukiamai sąveikaujant net aplinkoje esant trikdžių, atsirandančių dėl greitai naudotojo judinamos kameros, okliuzijų aplinkoje ir pan.

2. Priklausomai nuo prieinamos informacijos, gautos išskyrus ir apdorojus požymius iš vaizdo ar jutiklių duomenų sujungimo įverčių, pasiūlyti skirtingi orientacijos ir pozicijos informacijos pasikliovimo atvejai, atsižvelgiant į Kalmano filtro inovacijos parametro sąlygas. Pasiūlytas hibridinis objekto sekimo metodas naudojant Kalmano filtrą pagerina objekto sekimo patikimumą ir eliminuoja atsirandantį delsimą požymių išskyrimo iš vaizdo atveju.

3. Sukurta papildytos realybės programa mobiliesiems įrenginiams, kurioje adaptuotas hibridinis objekto sekimo metodas naudojant Kalmano filtrą. Sprendimas pritaikomas mobiliuosiuose įrenginiuose, turinčiuose akselerometrą, giroskopą ir magnetometrą.

4. Dalis atlikto tyrimo rezultatų panaudoti *Erasmus IP* projekte „Virtual bridge construction modelling and demonstration in augmented reality environment“. Tarptautinio projekto dalyviai: Klaipėdos valstybinė kolegija, Didžiosios Britanijos *Leeds Metropolitan* universitetas, Bulgarijos *Varna Free* universitetas, 2014 m.

5. Rezultatai panaudoti mokslo, inovacijų ir technologijų agentūros projekte „Inovatyvaus verslo kūrimo skatinimas (INOVEKS)“, 2014 – 2015 m., pateikiant patentinę paraišką disertacijoje gautų jutiklių duomenų sujungimo tyrimo rezultatų pagrindu. Pareiškėjas – Edgaras Artemčiukas. Išradimo pavadinimas – „Sferos formos sąveikos įrenginys“. Patento paraiškos Nr. 2015 063. Paraiškos pateikimo data: 2015-07-24. Būsena: taisomas. Realizaciją galima pažiūrėti: *https://www.ourtechart.com/augmented-reality/demo/spherical-form-interaction-device/.*

Ginamieji teiginiai

1. Siekiant užtikrinti tikslų objekto sekimą vaizde ir nepertraukiamą virtualaus turinio atvaizdavimą papildytos realybės aplinkoje, tikslinga naudoti ne tik kompiuterinės regos metodus, bet ir jutiklių duomenų sujungimą, kai jutikliai yra pritvirtinti prie kameros.
2. Pasiūlytas hibridinis objektų sekimo metodas naudojant Kalmano filtrą leidžia išvengti požymių ištraukimo bei apdorojimo iš vaizdo ir jutiklių duomenų sujungimo pagrindu naudojamų sekimo metodų sutrikimų, kurie atsiranda dėl sekamo objekto transformacijų vaizde, išorinių aplinkos sąlygų, jutiklių matavimų, pritvirtintų prie kameros, triukšmo, nuokrypių ar kitų iškraipymų.
3. Pateiktas hibridinis objektų sekimo metodas naudojant Kalmano filtrą leidžia užtikrinti patikimus sekamo objekto pozicijos ir orientacijos įverčius tiek imituotų duomenų atžvilgiu, tiek taikant papildytos realybės aplinkoje realaus naudojimo sąlygomis greitai judant kamerai ir esant sekamo objekto okliuzijomis vaizde.

Darbo rezultatų aprobavimas

Mokslinės publikacijos *Thomson Reuters* žurnaluose:

- Artemciukas, E., Plestys, R., Andziulis, A., Gerasimov, K., Zulkas, E., Pasviestis, L., Krauze, A. (2012). Real-time Control System for Various Applications using Sensor Fusion Algorithm. *Elektronika ir elektrotechnika*, Vol. 18, No. 10, p. 61–64, ISSN 1392-1215, DOI: 10.5755/j01.eee.18.10.3064.

- Artemciukas, E., Sakalauskas, L., Zulkas, E. (2016). Kalman Filter for Hybrid Tracking Method in Augmented Reality. *Elektronika ir elektrotechnika*, Vol. 22, No. 6, p. 73–79, ISSN: 1392-1215, DOI: 10.5755/j01.eie.22.6.17228.

Mokslinės publikacijos *ISI Proceedings*:

1. Lukosiunas, E., Bulbenkiene, V., Andziulis, A., Artemciukas, E. (2011). An ultrasonic tracking method for augmented reality. *Proceedings of the 17th International Conference on Information and Software Technologies*, Kaunas, Lithuania, p. 170–173.
2. Zulkas, E., Artemciukas, E., Dzemydiene, D., Guseinoviene, E. (2015). Energy consumption prediction methods for embedded systems. *Tenth International Conference on Ecological Vehicles and Renewable Energies (EVER)*, Monte Carlo, p. 1–5, ISBN 978-1-4673-6784-4, DOI: 10.1109/EVER.2015.7112932.

Mokslinės publikacijos kituose recenzuojamuose žurnaluose:

1. Artemčiukas, E., Sakalauskas, L. (2014). Vaizdo apdorojimo metodų tyrimas ir taikymas papildytos realybės sistemose. *Jaunųjų mokslininkų darbai*. Nr. 1 (41), p. 91–98, ISSN 1648-8776.
2. Artemčiukas, E., Sakalaukas, L. (2014). Jutiklių orientacijos duomenų integracija papildytos realybės technologijoje. *Mokslas – Lietuvos ateitis. Elektronika ir elektrotechnika*, Vilnius: Technika, Nr. 6 (2), p. 172–177, ISSN 2029-2341 (print) / ISSN 2029-2252 (*online*).
3. Artemčiukas, E., Sakalauskas, L. (2014). *Leap Motion* valdiklio taikymas papildytos realybės technologijoje. *Technologijos mokslo darbai Vakarų Lietuvoje IX*, Nr. 9, p. 10–15, ISSN 1822-4652.

Dalyvavimas tarptautinėse konferencijose:

1. Artemciukas, E. Real-time Control System for Various Applications using Sensor Fusion Algorithm (2012). *The 16th International Conference ELECTRONICS 2012*, Palanga, Lithuania, 18th-20th June.
2. Artemciukas, E. Kalman Filter for Hybrid Tracking Method in Augmented Reality (2016). *The 20th International Conference ELECTRONICS 2016*, Palanga, Lithuania, 13th-15th June.

Dalyvavimas nacionalinėse konferencijose:

1. Artemčiukas, E. (2013). Computer vision methods research and application in augmented reality systems. *5-oji Lietuvos jaunųjų mokslininkų konferencija „Operacijų tyrimas ir taikymai"*, Šiaulių universitetas.
2. Artemčiukas, E. (2014). *Leap Motion* valdiklio taikymas papildytos realybės technologijoje. *IX-oji mokslinė konferencija „Jūros mokslai ir technologijos*, Klaipėdos universitetas.
3. Artemčiukas, E. (2015). 3D virtualaus turinio manipuliavimas papildytos realybės technologijoje. *Penktoji jaunųjų mokslininkų konferencija: „Tarpdalykiniai tyrimai fiziniuose ir technologijos moksluose"*, Lietuvos mokslų akademija.

Disertacijos struktūra

Disertaciją sudaro įvadas, 3 skyriai, bendrosios išvados, literatūros ir priedų sąrašas. Disertacijos apimtis: 107 puslapiai, 109 numeruotos formulės, 46 paveikslai ir 3 lentelės. Literatūros sąrašą sudaro 118 šaltinių.

Įvade aprašyta mokslinio tyrimo dalykinė sritis, nagrinėjamos problemos aktualumas, tyrimo objektas, tikslas, uždaviniai, mokslinis naujumas bei jo reikšmė, rezultatų praktinė reikšmė, ginamieji teiginiai ir disertacijos rezultatų aprobavimo sąrašas.

1 skyriuje atliktas požymių išskyrimo iš vaizdo ir apdorojimo metodų tyrimas, siekiant išsiaiškinti šių metodų tinkamumą plėtojant papildytos realybės sistemas. Skyriuje pateikiami šiuo metu kai kurie plačiausiai naudojami požymių aptikimo ir aprašymo metodai, kurie leidžia išspręsti dalinės okliuzijos problemas ir tinkamai atvaizduoti virtualų turinį papildytos realybės aplinkoje. Tyrime atliktas našumo palyginimas pagal atkartojimo kriterijų naudojant skirtingo tipo vaizdų transformacijos rinkinius, tikrinant specifines vaizdų poras. Įvertintas santykinis požymių išskyrimo ir apdorojimo metodų greitis ir tinkamumas papildytos realybės sistemose.

2 skyriuje atliktas jutiklių orientacijos duomenų sujungimo tyrimas ir integracija papildytos realybės srityje. Nagrinėjamas gradientinio nusileidimo metodo (kvaternionų pagrindu) taikymas mikroelektromechaninių jutiklių duomenims, norint tiksliau įvertinti kameros orientaciją trimatėje erdvėje. Tyrime siekiama eliminuoti pavienių jutiklių matavimo duomenų triukšmą ir pagerinti kameros orientacijos sekimo tikslumą, patikimumą, kur virtualus turinys atvaizduojamas papildytoje realybėje nenaudojant požymių iš vaizdo išskyrimo ir jų apdorojimo metodų. Demonstruojamas orientacijos įvertinimo sprendimas pritaikytas ne tik iš kameros sekimo aspekto ir taikymo papildytos realybės srityje, bet ir plėtojant sąveikos įrenginį. Nagrinėjamas Kalmano filtro panaudojimas sekant objektų orientaciją. Pateikta detali Kalmano filtro analizė, praktinis taikymas gautiems jutiklių matavimų duomenims, kurie išreikšti kvaternionais.

3 skyriuje pasiūlytas hibridinis objekto sekimo metodas papildytos realybės sistemose, naudojant Kalmano filtrą. Tyrime atlikti eksperimentai su imituotais objekto pozicijos bei orientacijos duomenimis požymių ištraukimo iš vaizdo ir apdorojimo bei jutiklių duomenų sujungimo atvejais. Rezultatai palyginti bei pateikti pasiūlyto metodo pagerinti aspektai objekto sekimo atžvilgiu. Hibridinis objekto sekimo metodas naudojant Kalmano filtrą adaptuotas mobiliesiems įrenginiams papildytos realybės daiktų interneto srityje.

Pateiktas priedų sąrašas su turiniu *CD* duomenų laikmenoje ir *Google Drive* diske.

BENDROSIOS IŠVADOS

1) Atlikus požymių išskyrimo ir klasifikavimo metodų analizę nustatyta, kad tiek klasifikavimo metodai, tiek požymių išskyrimo metodai sprendžia vaizdo požymių pertekliaus problemą, transformuojant perteklių į sumažintą požymių kiekį, kuris vis dar suteiktų pakankamai informacijos, norint atpažinti ir sekti konkretų objektą aplinkoje. Nėra vieno universalaus požymių išskyrimo metodo, kur objekto sekimo uždavinių atlikimas tiktų bet kuriai taikymo sričiai, nes egzistuoja kiti reikalavimai skirtingose taikymo srityse, skiriasi konkretaus sekamo objekto savybės ir aplinkos sąlygos, nuo kurių priklauso požymių prieinamumas. Pagal atliktus greitaveikos eksperimentus nustatyta, kad požymių išskyrimas ir sutapdinimas vyksta daugiau nei 4 kartus lėčiau už *SURF* metodą ir 11 kartų lėčiau už *FAST* metodą. Papildytos realybės sistemose objekto sekimas turi būti vykdomos realiu laiku. Įvertinus *SIFT*, *SURF* ir *FAST* požymių išskyrimo metodų stabilumą pradinio vaizdo mastelio keitimo atveju *SIFT* atkartojimo kriterijus yra 15–30% didesnis už *SURF* metodą ir 35–55% didesnis už *FAST*. Vaizdą pasukant *SIFT* metodo atkartojimo kriterijus didesnis 40% lyginant

tiek su *SURF*, tiek *FAST* metodais. Vaizdą pastumiant *SIFT* ir *SURF* atkartojimo kriterijaus rezultatai panašūs, bet 4–20% didesni už *FAST* metodą.

2) Analizė parodė, kad naudoti pavienių jutiklių matavimų duomenis, objektų orientacijai nustatyti – nėra patikimas sprendimas. Analitiniu-eksperimentiniu būdu ištirti akselerometro, giroskopo ir magnetometro jutikliai, taip pat jungtinis šių jutiklių informacijos naudojimo atvejis, pritaikius kvaternionų išraiškoms gradientinį nusileidimo metodą, kai jutiklių masyvas tvirtinamas prie kameros. Pagal atliktų eksperimentų ir skaičiavimų rezultatus nustatyta, kad naudojant gradientinio nusileidimo metodą, galima kompensuoti atskirų jutiklių trūkumus, padidinti įvertintų orientacijų tikslumą bei patikimumą, išvengiant nuokrypių, triukšmo jutiklių matavimų atvejais bei sumažinant delsimą kompiuterinės regos metodų atvejais. Nustatyta, kad tikslinga naudoti jutiklių duomenų sujungimą, siekiant papildyti nesamus objekto sekimo įverčius arba juos pagerinti. Šie įverčiai gauti kompiuterinės regos pagrindu, esant sekimo sutrikdymams, kylantiems dėl didelio kameros judėjimo greičio ar netinkamai įvertintos padėties informacijos dėl skirtingų vaizdo transformacijų.

3) Pasiūlytas hibridinis objekto sekimo metodas naudojant Kalmano filtrą, kurį sudaro tiek jutiklių duomenų sujungimo (sekti kamerą), tiek kompiuterinės regos (sekti vaizdą) pagrindu imituota orientacijos ir pozicijos informacija. Hibridinio objektų sekimo metodo eksperimentų rezultatai palyginti su imituotais kompiuterinės regos bei jutiklių duomenų sujungimo metodo duomenimis. Pasiūlyto hibridinio objekto sekimo metodo naudojant Kalmano filtrą orientacijos įvertinimo paklaida siekia tik 0,24%, o tik jutiklių duomenų sujungimo bei tik kompiuterinės regos atveju – 0,30%. Hibridinio objekto sekimo metodo naudojant Kalmano filtrą pozicijos įvertinimo paklaida siekia 0,96%, tik jutiklių duomenų sujungimo atveju – 13,06%, o tik kompiuterinės regos atveju – 19,75%.

4) Pasiūlytas hibridinis objektų sekimo metodas naudojant Kalmano filtrą pritaikytas mobiliesiems įrenginiams leidžia ne tik nepertraukiamai atvaizduoti daiktų internetui skirtą vartotojo sąsają papildytoje realybėje, bet atskira hibridinio objekto sekimo metodo dalis gali būti adaptuota sąveikos įrenginių plėtojimui, kuriais praplečiamas ir gerinamas sąveikavimas su skaitmeniniu turiniu ar kita technine įranga, įgalinami skirtingi veikimo režimai bei taikymo galimybės, todėl pasiūlytas hibridinis objekto sekimo sprendimas pasižymi universalumu.

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Summary of Doctoral Dissertation
Physical Sciences (P000)
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